



ULTRASONICS  
AND THEIR SCIENTIFIC AND  
TECHNICAL APPLICATIONS



# ULTRASONICS

## AND THEIR SCIENTIFIC AND TECHNICAL APPLICATIONS

BY

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## AUTHOR'S PREFACE

IT is rare for a physical phenomenon to have found within a few years so many applications in all branches of science and technology as ultrasonics. Almost every number of the scientific and technical journals concerned has printed in the last few years a paper dealing with the phenomena of high-frequency sound waves or their application. At the present time this body of literature amounts to about 450 single publications, and this fact has led to the need for a general account of ultrasonic processes. I was therefore glad to accept the invitation of the VDI-Verlag, and I have tried to give a coherent account in the present book of the position to-day in ultrasonic research, and of its chief results.

In doing so I have given the chief place to experimental results, and have only taken account of theoretical work, which is in some branches very extensive, when this has been necessary to a proper understanding of the subject. My main purpose has been to give those interested in ultrasonics a guide to the subject, showing what has been done in this field up to the present. The material being so extensive it was not possible to treat all of it with the same amount of detail, but the reader will at least find a reference to the original publication.

I have to express my thanks to the following firms for illustrations and other subject-matter: The Atlas-Werke in Bremen, Debeg in Hamburg, Electroacustic in Kiel, Radio-Loewe in Berlin, Siemens-Reiniger-Veifa, and Steeg & Reuter in Bad Homburg. My especial thanks are due to Dr H. J. Goehlich, who gave me great assistance by reading the manuscript and proofs.

This English edition is an unabridged translation of the book published by the VDI-Verlag in Berlin in July 1937. Papers dealing with ultrasonics which have been published since then have been grouped at the end of the book under headings, so that the reader can acquaint himself with the latest progress which

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has been made. An addition is made in the English edition dealing with the application of ultrasonics to television. For this I am indebted to Dr H. Stafford Hatfield, to whom are also due my special thanks for the excellent English translation.

L. BERGMANN

BRESLAU, June 1938

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## INTRODUCTION

THE term 'ultrasonics' is used in acoustics to denote the frequencies which are beyond the limits of hearing of the human ear—that is to say, frequencies of about 20,000 (20 kHz) and upwards. By using the modern methods of generation to be described, it is possible to produce ultrasonic vibrations up to a frequency of about  $5 \times 10^5$  kHz. Expressed in wave-lengths this means that ultrasonic waves in air (velocity of sound  $v = 330$  m/s) cover a range of 1.6 cm to  $0.6 \times 10^{-4}$  cm, in liquids ( $v \approx 1200$  m/s) a range of 6 cm to  $2.4 \times 10^{-4}$  cm, and in solids ( $v \approx 4000$  m/s) a range from 20 cm to  $8 \times 10^{-4}$  cm. The shortest ultrasonic waves are therefore already in the order of magnitude of the waves of visible light. By reason of the smallness of the wave-length it has been found possible to make use of ultrasonics in the most various directions. Many investigations of sound vibrations, and particularly measurements of velocity, may be made in a much smaller space by the use of ultrasonics than with the audible vibrations formerly used, without the influence of boundary walls making itself felt. The laws of sound valid for the audible range are also true for the ultrasonic range, though in the latter case further phenomena appear which had not previously been observed in the audible way.



## CHAPTER I

### THE GENERATION OF ULTRASONICS

(a) **Mechanical Generators.** Ultrasonic waves may be produced in air, as was already shown by König (268) in 1899, by means of small tuning-forks with prongs only a few millimetres long, up to frequencies of about 90 kHz. The waves produced

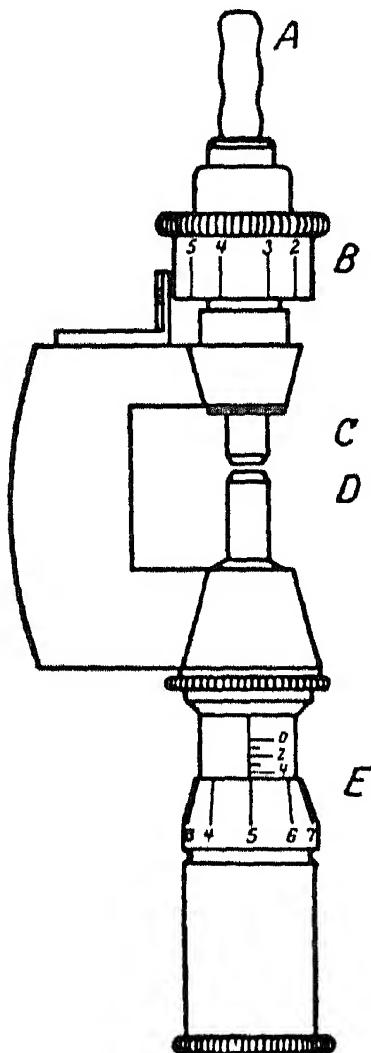


FIG. 1. Galton whistle.

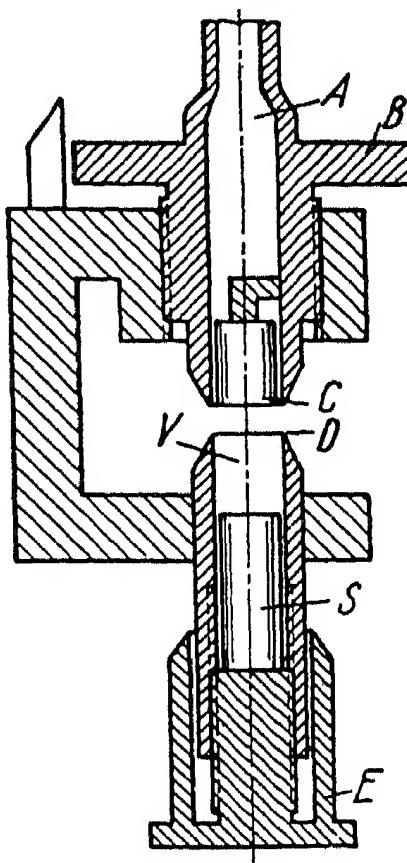


FIG. 2. Section through a Galton whistle.

in this way, however, are so strongly damped and of such small energy that they are of no use for practical purposes.

**1. The Galton Whistle.** The Galton Whistle, designed by Edelmann (137), is of greater importance, especially for physiological purposes, as it gives vibrations, very constant both in amplitude and frequency, up to about 100 kHz. Fig. 1 shows

the usual design of a Galton whistle, fig. 2 being a section. The current of air is sent through the nozzle *A* onto a circular slit *C*, out of which it streams against a sharp circular knife-edge *D*. This sets the air in *V* in vibration. By turning the drum *E*, the volume of air in the whistle may be changed by means of a movable piston *S* (closed pipe of variable length *l* mm). A second micrometer screw *D* allows the size of the gap between *C* and *D* to be adjusted to a favourable value. The wave-length of the sound is calculated from  $\Lambda = 4l + k$  [mm];  $k$  is a constant, which changes with the pressure at which the air is blown in. For example,  $k = 7.3$  mm for  $p = 30$  cm of water,  $6.2$  mm for  $70$  cm, and  $4.7$  mm for  $408$  cm. The frequency of the vibrations in air is then got from  $N = 331,800 \sqrt{1 + 0.00367t/4l + k}$ , if the length of the whistle is measured at the temperature *t*. Since the frequency, as we see, is dependent on the blowing pressure, work with the Galton whistle needs a certain amount of care, but if the pressure is kept constant the whistle gives a good standard of frequency for high frequencies, and is still much used for this purpose on account of its simplicity (130, 196, 418, 426).

**2. The Gas Current Generator.** For attaining considerably greater energies of vibration in air, up to about 50 W of sound

energy, Hartmann (181 to 185) built an air current generator (fig. 3). If a current of air is allowed to issue from a nozzle *D* with an excess pressure of 0.9 atm, a periodical structure (shown dotted in fig. 3) is formed in the air streams; this was first observed by Mach and Salcher (308). If a Pitot tube is used to measure the pressure in the jet at different distances from the mouth of the nozzle, we get a distribution of pressure such as that shown by the curve *k* in fig. 3. The regions of rise of pressure  $a_1 b_1$ ,  $a_2 b_2$  are intervals of instability in the jet and make possible the production of air waves, when a hollow body, serving as an oscillator, is brought into these unstable positions. The oscillator is periodically filled with an over-pressure of air, and in the intervals this air is forced out again, whereby an oscillation is produced. The

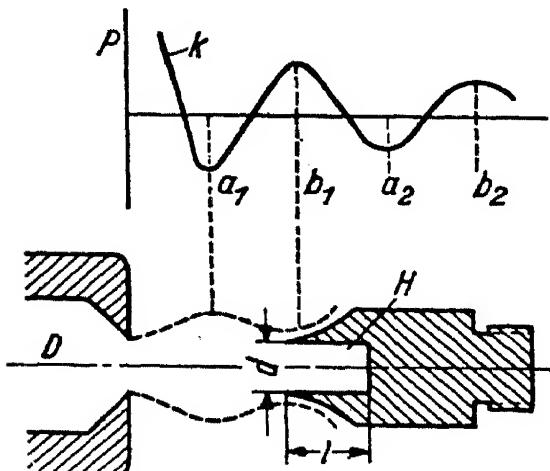


FIG. 3. Gas current vibration generator (Hartmann).

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frequency of the air pulses, and therefore of the sound waves sent out from the opening of the oscillator, is determined by the dimensions of the latter. If  $l$  is the length of the oscillator space, and  $d$  its diameter, which is best chosen equal to the diameter of the jet, we get the wave-length  $\Lambda$  of the sound very approximately from  $\Lambda = 4(l + 0.3d)$ . If, for example, we make  $l = d = 1$  mm, we get a wave-length of 5.2 mm—that is, a frequency in air of about 63 kHz.

Fig. 4 shows a longitudinal section of Hartmann's form of this generator. The nozzle  $T$  is fixed by means of two nuts

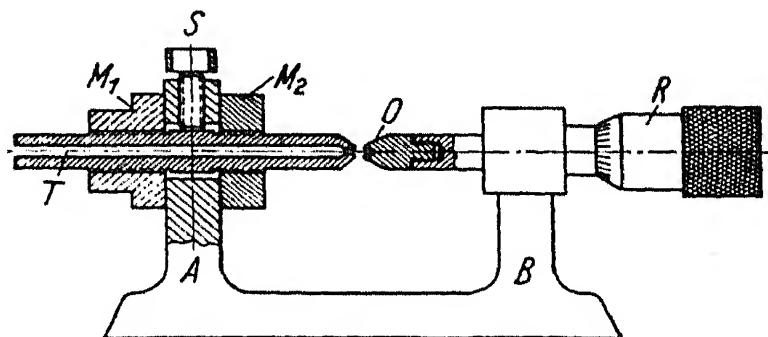


FIG. 4. Construction of Hartmann generator.

$M_1$  and  $M_2$  to the base  $A$ , and may be set, when one nut is loosened, by means of three positioning screws  $S$  (in section, fig. 4, only one is shown), exactly opposite the opening of the oscillator  $O$ . The oscillator, which may be changed, is fixed to the front end of a micrometer screw  $R$ , by which it may be adjusted to the correct position in the air jet. Generators of this kind produce oscillations up to about 120 kHz; by using hydrogen instead of air this may be increased to about 500 kHz, the velocity of sound in this gas being about four times greater. A recent publication (184) gives the efficiency as about 5 per cent.

3. Holtzmann's Generator. It is well known that sound waves may be produced by getting a glass or metal rod to vibrate lengthways; if a rod of length  $l$  is clamped in the middle, its fundamental elastic oscillation gives a frequency

$$N = \frac{1}{2l} \sqrt{\frac{981 \times 10^5 E}{\rho}}, \text{ where } E \text{ is the modulus of elasticity in}$$

$\text{kg/mm}^2$  and  $\rho$  the density of the material of the rod in  $\text{g/cm}^3$ . Holtzmann (220) has described a method of exciting in such a rod powerful elastic oscillations by a mechanical method, so that its free end becomes a source of sound waves. In fig. 5

the rod  $S$  is formed by a glass tube 6 to 8 mm in diameter, clamped in the middle, one end being rounded to a bulb. Two endless bands of soft leather, covered on the outside with silk, run over the two large pulleys  $A$  and  $A'$ , and the pairs of small pulleys  $a$  and  $a'$ , these being fixed to a common base plate. Between the pulley pairs  $a$  and  $a'$  are two pairs of smaller pulleys held by springs against the bands, and pressing them against the glass tube on both sides, whereby powerful oscillations are excited in it.

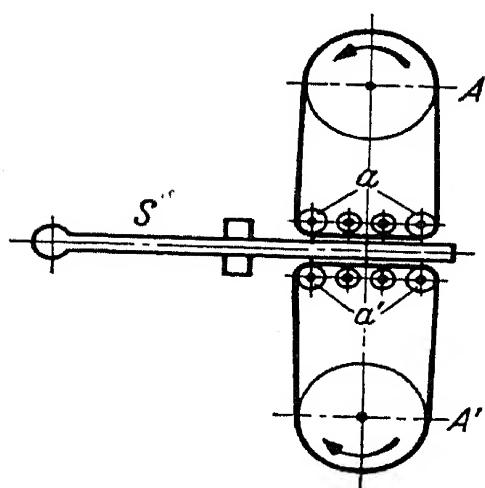


FIG. 5. Holtzmann's ultrasonic generator.

Holtzmann produced by means of this arrangement, using a glass tube 7.5 cm in length, a frequency of about 33 kHz, the power of the waves being about 150 times greater than that of the standard Galton whistle.

(b) **Thermal Generators.** Thermal generators are of hardly any importance to-day, and are only mentioned for the sake of completeness. Altberg (3) generated sound waves up to a frequency of 300 kHz by means of a spark gap fed by a damped oscillatory circuit. Sparks of this sort naturally send out a mixture of a great number of frequencies, from which the one desired has to be separated by some such device as a diffraction grating (333). But the amplitude of such waves is very inconstant and dependent on a number of conditions, some of which are uncontrollable. At the present day, ultrasonics produced by sparks in this way are used only in investigations of the propagation of sound, as in experiments on models, for example, for the acoustics of buildings (337), or for examining the distribution of sound in musical instruments (147, 148).

Much more constant ultrasonics are produced by a direct current arc, with alternating current superimposed on it. This produces a periodical development of heat in the arc, and so a periodical change in its volume. If the alternating current is greater than the direct current, sound of double the frequency is produced. Instead of feeding in a separate alternating current, the arc itself may be used to generate electric oscillations (131, 132). In this way, Diëckmann (128), using a Poulsen arc in illuminating gas, generated sound waves up to

a frequency of 780 kHz. As the frequency of the oscillatory circuit may be changed continuously by changing the capacity, continuous change of the frequency of the generated sound is possible, an advantage unfortunately not possessed by most sound sources. Palaiologos (344), using a valve for generating the alternating current, was able to get sound waves up to 2000 kHz from an arc in air.

(c) **The Magnetostriiction Generator.** The ultrasonic generators now to be described are based on the transformation of alternating electric currents into sound vibrations. The electrical sound generators commonly used in the audible range (telephones and loudspeakers) are of no use for ultrasonic purposes, as the natural frequencies of their vibrating parts are too low, and cannot for technical reasons be increased to the necessary extent. In the few cases in which the natural frequency can be raised sufficiently, as, for example, in the metal strip telephone, the efficiency of transformation of electric into sound energy falls off very greatly. Mülwert (329) made a strip telephone of this type, giving frequencies up to 200 kHz, but having a sound output of only 0.02 W.

The electrical generators most used at the present time for ultrasonics are therefore based on the principle of using high-frequency electric oscillations, which are easily produced by means of valves, for exciting suitably formed bodies to vibration in their natural elastic periods. One possible method is to make use of magnetostriiction.

1. **The Magnetostriiction Effect.** If a rod or tube of ferromagnetic material is brought into a magnetic field parallel to its length, the latter is changed slightly; this change of length is independent of the sign of the field, and may be either a decrease or increase, depending on the nature of the material, its previous treatment, the degree to which it was previously magnetized, and the temperature. This phenomenon is known as 'magnetostriiction,' or as the Joule effect (240), after its discoverer. The changes of length so produced are comparatively small—the relative change of length being of the order of one part in a million—and can only be determined by the microscope or by an optical lever. Fig. 6 shows the change of length of various ferromagnetic substances plotted against the magnetic field strength. Only rods of nickel and annealed

cobalt show a simple and regular behaviour, in the form of a decrease in length increasing with the field; other materials exhibit a turning point on the curve, at which the sign of the change in length with increase in field is reversed.

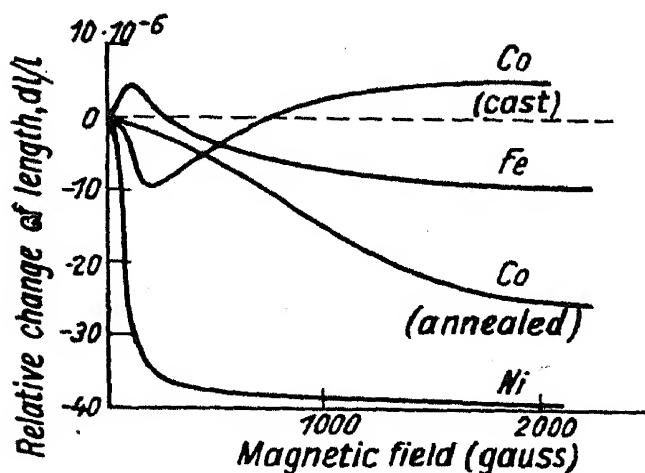


FIG. 6. Change of length by magnetostriiction.

the rod an E.M.F. is induced in it by an elastic deformation of the rod.

**2. The Magnetostriiction Oscillator.** If a nickel rod, for example, is brought into an alternating magnetic field it is shortened periodically by magnetization. It is easy to see that if the rod is not previously magnetized it will vibrate with double the frequency of the alternating field, whereas if it is suitably premagnetized, the mechanical change in length will be in step with the alternating frequency. If there is resonance between the natural elastic period of the rod and the frequency of the alternating current, the amplitude of the oscillation will be a maximum, and sound waves of the same frequency will be sent out from the end of the rod. The frequency of the sound may be calculated from the formula on p. 3, when the rod is excited with its fundamental frequency. Rods and tubes suitably clamped may be also set in vibration with overtones, though the amplitude attainable is less. The natural frequency  $N$  of a rod of length  $l$  may be represented by the

$$\text{equation } N_k = \frac{k}{2l} \sqrt{\frac{E}{\rho}}, \text{ where } E \text{ and } \rho \text{ are the elastic constant}$$

and the density of the material, and  $k = 1, 2, 3 \dots$  are the order numbers of the overtones. In the following we will take the fundamental as the overtone of the first order, so that for  $k = 1$  the equation becomes that already given on p. 3. The

change in length with increase in field is reversed. The magnetostriction effect decreases with rise of temperature, and disappears at the Curie point. Like most physical phenomena it is reversible. If a previously magnetized rod of nickel is stretched the magnetization of the rod is decreased; if the rod is compressed in the direction of its length the magnetization is increased. If a coil is put round

calculation gives us a value of 20.4 kHz for the natural frequency of a nickel rod 12.5 cm long.

The amplitudes which can be produced by magnetostriiction generators working on the fundamental period are of the order of  $10^{-4} l$ , where  $l$  is the length of the rod. The highest frequencies obtainable with some degree of power are of the order of 60 kHz. In this case the length of a nickel rod excited in the fundamental is only about 4 cm. With shorter rods it is already difficult to get the fundamental oscillation, and it is necessary to have recourse to the overtones with a resulting loss in intensity. Pierce (363,

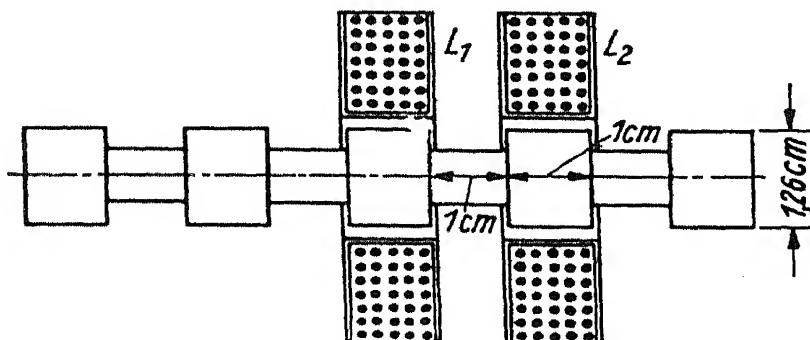


FIG. 7. Magnetostriiction rod for very high frequencies, about 300 kHz (Pierce).

(364) has described a form of rod suitable for specially high frequencies, and shown in fig. 7. A steel rod, 9 cm long and 1.26 cm diameter, has four grooves turned in it at equal distances, each groove being 1 cm long and 1.32 cm deep. Two sections of the rod, separated by a groove, are placed in the axes of the anode ( $L_1$ ) and grid ( $L_2$ ) coils of a valve generator. With the dimensions given we get a natural frequency of the whole system of 295.48 kHz; as the velocity of sound in the rod is 5430 m/s, this frequency corresponds to the fundamental of a rod  $54300 : 2 \times 295,480 = 0.918$  cm length. This is about 10 per cent. less than the actual length of the cylindrical sections of the rod.

Pure nickel and various nickel alloys have been found to give good results as material for rods and tubes. Pierce recommends an alloy of 36 per cent. nickel and 64 per cent. iron (Invar), and also what is known as monel metal, an alloy of 68 per cent. nickel and 32 per cent. copper, with small amounts of iron, silicon, manganese, and carbon.

The dynamic behaviour of ferromagnetic rods of this sort in an alternating magnetic field has been investigated by Black (69).

If a thin-walled nickel tube is filled with a material in which

the velocity of sound is less, for example lead, the natural frequency of a generator of given size may be considerably reduced. By using two metals for outer and inner parts, having equal temperature coefficients of opposite sign, vibrators with the smallest possible frequency change with temperature may be constructed (363).

Substances which are not ferromagnetic, and insulators, may likewise be used (Kunze, 279) as magnetostriction oscillators by giving the rods made of them a coating of a magnetostrictive material, for example nickel, or by making the oscillator out of laminæ coated on one or both sides with a thin layer of magnetostrictive material. In the latter case, the losses by eddy currents are reduced to a minimum.

In the rods or tubes so far described, set in longitudinal oscillation by magnetostriction, sound is emitted only from the ends of the rod. But the problem frequently arises of sending sound out evenly in all directions in a plane, for example in submarine work, or of giving some special characteristic to the radiation from the generator. Uniform emission of sound in all directions in a plane may be attained by using a circular ring set by magnetostriction into elastic oscillation in such a way that the ring forms a circle with periodically changing radius, the sections of the ring moving only radially. Sound is then radiated from the outer edge of the ring in a radial direction. The natural frequencies of a ring vibrating in this way are given by

$$N_k = \frac{1}{2\pi r} \sqrt{\frac{E}{\rho}} \sqrt{1 + (1 - k)^2} = \frac{v}{2\pi r} \sqrt{1 + (1 - k^2)} \quad (k = 1, 2, \dots),$$

where  $r$  is the mean radius of the ring,  $E$  the modulus of elasticity,  $\rho$  the density, and  $v$  the velocity of sound in the material of the ring. A ring of this sort may be excited by a toroid winding through which an alternating current of resonance frequency is sent. As we see from the equation for the natural frequency, this is dependent in the case of a given material only on the diameter of the ring. If we wish to lower the natural frequency of a ring of given diameter or work with a ring of smaller radius at a given frequency, we may give the ring teeth on either its outer or inner edge, or on both, as shown in fig. 8, whereby the weight of material in oscillation is increased without change in the elastic control (Kallmeyer, 242). In order to avoid eddy current losses a ring

this sort is best built up of laminations insulated from one another. The magnetic winding may be suitably placed in the slots of the ring. Kallmeyer (241) also describes magnetostriction oscillators (fig. 9), in which the vibrating surface is

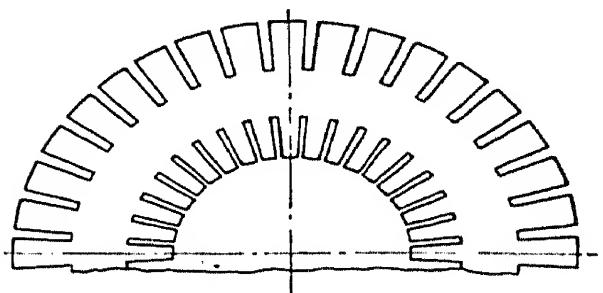


FIG. 8. Magnetostriction ring vibrator (Kallmeyer).

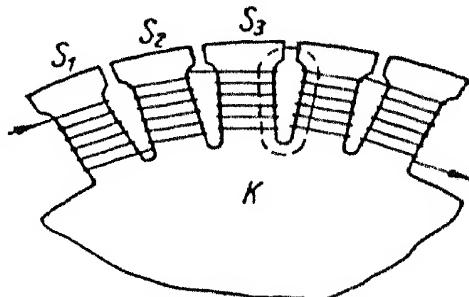


FIG. 9. Magnetostriction vibrator (Kallmeyer).

formed by the ends of a series of longitudinally oscillating spokes, which are fixed to a mass  $K$  which may be taken as rigid. Single spokes are provided with a winding connected in such a way that the magnetic flux is of opposite sign in adjacent spokes, in order to produce a closed magnetic circuit. By giving the ends of the spokes special shapes, the sound-radiating characteristics of the system may be changed. This may also be effected by exciting separate spokes with alternating currents of different phases.

**3. The Design of a Magnetostriction Generator.** The rods or tubes may be set in vibration in different ways. Pierce (363, 34), who was one of the first to make a magnetostriction generator, uses a reaction circuit together with a valve, as shown in fig. 10. The rod  $S$  is clamped in the middle between two knife edges, and round it on the right-hand side is the coil  $L_1$ , forming with the condenser  $C$  an oscillating circuit connected to the anode of the valve  $R$ . On the left hand of the rod we have the coil  $L_2$  connected to the grid and filament of the valve. In the case of both coils the internal diameter is great enough to allow the rod to move lengthways freely. This circuit gives us self-excitation of oscillation by the reciprocal effects of magnetostriction, for as the elastic deformation of the rod produces a change in its magnetization, an E.M.F. is induced in the coil  $L_2$ , which regulates by means of the grid the anode current of the valve. Oscillation is indicated

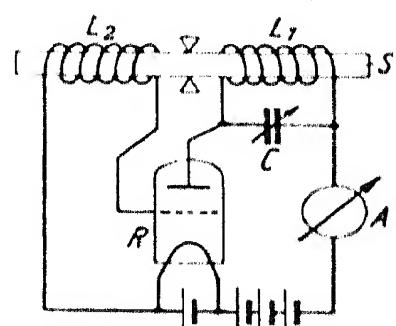


FIG. 10. Circuit of a magnetostriction vibrator (Pierce).

by a rise in the anode current shown on the milliammeter  $A$ . In this apparatus the premagnetization of the rod is produced by the steady anode current or by a permanent magnet placed near the rod.

The working of the apparatus is somewhat more readily seen if we do not maintain the oscillation by means of the vibrating rods. In fig. 11 one end of the nickel tube  $N$  is in the axis of the coil  $L_1$  and rests on knife edges  $S_1$  and  $S_2$  placed at the nodes of vibration, so that it can vibrate in the second overtone as its lowest frequency.

This coil forms together with the variable capacity  $C$  an oscillating circuit, which is maintained by the valve  $R$  connected to form a Hartley circuit. Since the coil in this circuit gets only alternating current, but not the anode current, separate premagnetization is necessary, this being provided by the coil  $L_2$ . The condition of oscillation is indicated by a separate circuit, the coil  $L_3$  of which is round the other end of the rod, and is connected in the well-known manner through a rectifier  $D$  with a direct current instrument. In order to avoid a direct influence of the oscillation of the Hartley circuit on the indicator circuit, Giebe

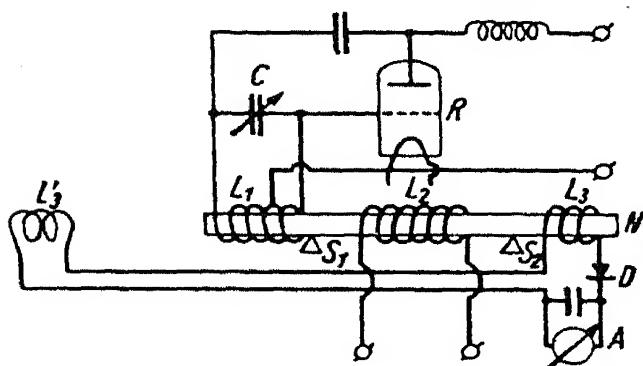


FIG. 11. Circuit of a magnetostriiction generator with premagnetization and indicator connections.

connected to form a Hartley circuit. Since the coil in this circuit gets only alternating current, but not the anode current, separate premagnetization is necessary, this being provided by the coil  $L_2$ . The condition of oscillation is indicated by a separate circuit, the coil  $L_3$  of which is round the other end of the rod, and is connected in the well-known manner through a rectifier  $D$  with a direct current instrument. In order to avoid a direct influence of the oscillation of the Hartley circuit on the indicator circuit, Giebe

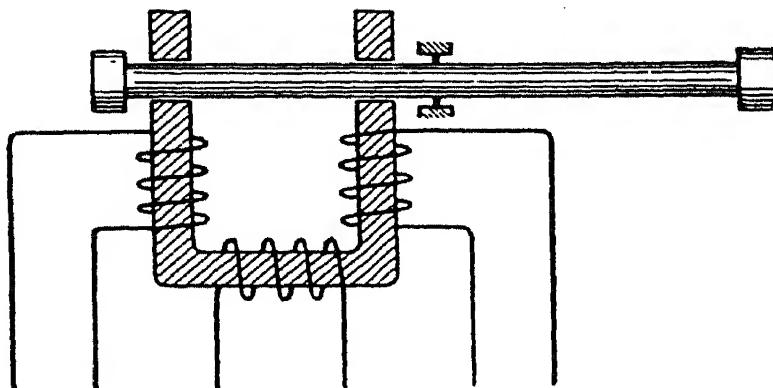


FIG. 12. Excitation of a magnetostriiction rod by means of a magnetic yoke.

and Blechschmidt (162) put an extra coil  $L'_3$  in the indicator circuit, which compensates for the inductive action of  $L_1$  on  $L_3$ .

As fig. 12 shows, the premagnetizing coil, the oscillating inductance, and the grid coil of fig. 7 may all of them be wound

a magnetic yoke applied to one-half of the vibrating rod. In order to get as large a radiation of sound as possible from the ends of the vibrating rod or tube, they may have fixed to them aluminium plates (fig. 12), but these must be sufficiently thick to vibrate only as pistons, and not to form nodes on themselves. It is advisable to avoid eddy current loss and the resultant rise of temperature by using for generators of considerable capacity only tubes as oscillators, which are then slit along their lengths.

The chief advantage of magnetostriction generators lies in the simplicity and cheapness of their construction. At low ultrasonic frequencies a considerable output of energy is possible without any danger of the destruction of the oscillating system even under temporary overload. The disadvantages lie in the upper limitation to the frequency, in a comparatively great dependence of frequency on temperature, and in a certain breadth of the resonance curve. This latter is caused by the change in the elastic constants of ferromagnetic substances with degree of magnetization, the so-called  $\Delta E$  effect. In the case of pure nickel, for example, measurements by Giebe and Blechschmidt (162) give the greatest value of the relative change of elastic constant 0.007 to 0.132, according as the material is hard or soft; the arithmetic decrement of the oscillation is correspondingly between  $4 \times 10^{-3}$  and  $2 \times 10^{-2}$ , as regards order of magnitude.

(d) The Piezoelectric Generator. The second method of transforming high-frequency electric oscillations into powerful mechanical oscillations is the piezoelectric. It is probably the most frequently used at the present day for generating resonances, and it alone allows us to attain the highest frequencies possible.

1. The Piezoelectric Effect. The brothers Curie (117) discovered in the year 1880 that many crystals when subjected to pressure or tension developed electric charges on definite crystal surfaces. This phenomenon, which could be readily produced, was named the piezoelectric effect. It was already known by these first experiments that the electric charges set free were proportional to the amount of the mechanical pressure or tension; the sign of the charges changes when a compression of the crystal is changed into a tension. The piezoelectric effect is observed in the following crystals: tourmaline, quartz, zinc fluoride, sodium chlorate, tartaric acid, cane sugar, Rochelle salt;

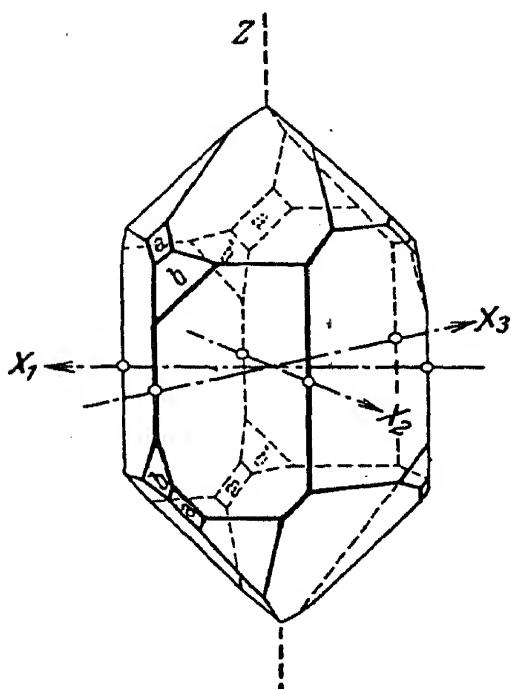
and later investigations (164, 200) have shown that it appears in many other crystals of the most various systems. The phenomenon is therefore not confined to a certain class of crystals, but the common property possessed by all crystals hitherto found to be piezoelectric is the presence of one or more polar axes or directions, or the absence of a centre of symmetry. A polar axis

or direction in crystallography is defined as an imagined direction in the crystal, the two ends of which are not equivalent—that is to say, cannot be interchanged. In other words, if the crystal is turned through  $180^\circ$  about an axis at right angles to the polar axis or direction, it cannot be made to coincide with its original position.

Let us make this point clearer by considering the crystal of quartz, which at the present time is the most used for piezoelectric purposes. Fig. 13 shows the typical form of a quartz crystal. It belongs to the trigonal system, and has three twofold polar axes which are indicated in fig. 13 by  $X_1$ ,  $X_2$ , and  $X_3$ .

FIG. 13. Quartz crystal.

These axes connect in every case two opposite edges of the six-sided prism, which, however, are not equivalent. This can be seen by the presence on one of the edges of the small faces marked  $a$  and  $b$ , which are missing on the opposite edge. The fourth axis  $Z$  is threefold and not polar, for by turning the crystals through  $180^\circ$  round one of the three  $X$  axes, it may be made to coincide with its initial position. Since the  $Z$  axis is an axis of optical symmetry, it is also described as the optical axis. The polar axes or directions are recognizable not only from the external form of the crystal but also by the fact that their two ends are quite different in physical and chemical respects. For example, the patterns produced by etching, and the rate at which etching takes place, are different at the two ends of a polar direction. When the crystal is stressed mechanically by pressure or tension, opposite electric charges appear at the ends of a polar axis or on surfaces at right angles to it. It is not necessary that the mechanical stress should be applied only in the direction of the



*x* axis; it is sufficient if one component of it is in this direction.

It would take us too far at this point to go in detail into the uses of the piezoelectric phenomenon from the point of view of molecular theory (325). We may say

much by way of explanation, that when pressure or tension is applied in the direction of a polar axis, the spacing between the ions out of which the crystal lattice is built up is not changed in the same proportion, so that if the units of the lattice carry electric charges, free charges must appear.

It is clear from what has been said that the maximum charges produced by mechanical stress only appear at the ends of a polar axis, and for this reason the plates or rods made use of in piezoelectric experiments are cut as far as possible out of the crystal in such a way that one pair of surfaces are at right angles to a polar axis, frequently called the piezo-axis. The manner of cutting a quartz crystal is shown in fig. 14 for a rectangular and a cylindrical plate. In the former, the edge *d* is parallel to the polar axis, the edge *b* parallel to the optical *Z* axis, and the length *l* parallel to the third coordinate axis *Y*.

Fig. 15 shows the direction of the axes in a piezoelectric quartz plate. In fig. 14, the rectangular plate is shown with its edges *b* and *d* parallel to the *Z* axis, and the length *l* parallel to the *Y* axis. A quartz plate cut in this way, represented again in fig. 15 without the crystal but with the directions of the axes, allows us to exhibit the following effects:—

FIG. 15. Direction of the axes in a piezoelectric quartz plate.

1. Pressure in the direction of the *X* axis charges the two surfaces *b* and *l*, normal to the *X* axis, positively or negatively respectively (longitudinal direct piezoelectric effect).

2. Tension in the direction of the *Y* axis charges the surfaces in the same way positively and negatively respectively (transverse direct piezoelectric effect).

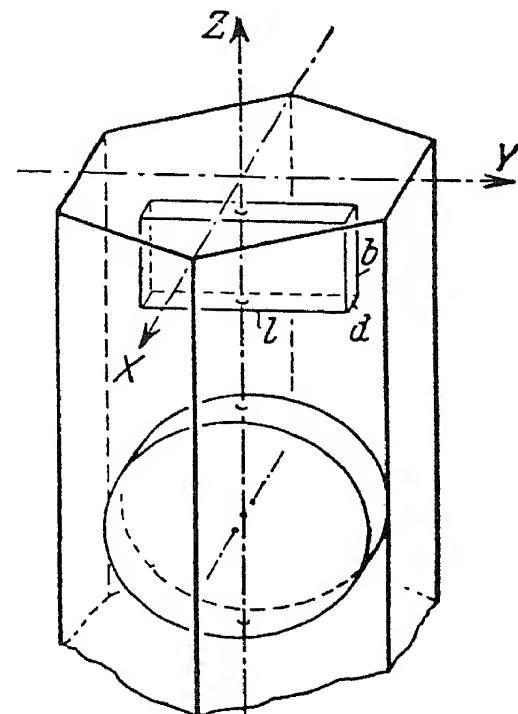
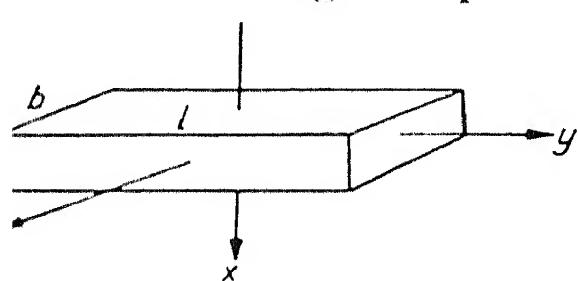


FIG. 14. Cutting of quartz plates and rods from a crystal.



1. Pressure in the direction of

3. Tension in case 1 and pressure in case 2 produce a reversal of sign of the electric charges on the surfaces  $b l$ .

4. Pressure or tension in the direction of the  $Z$  axis gives no piezoelectric effect whatever.

These direct piezoelectric effects are likewise reversible. The reciprocal piezoelectric effect was predicted in 1881 by Lippmann (290) from thermodynamic considerations. It was shortly afterwards discovered in the case of quartz by the brothers Curie (118). The reciprocal piezoelectric effect is exhibited as follows: If a piezoelectric crystal is brought into an electric field of force, in such a way that the direction of the field is the same as the direction of a piezoelectric axis, the crystal is made to contract or expand in certain directions. An expansion in the direction of an electric axis occurs, for example, when the electrodes on the surfaces at right angles to the electric axis are given charges of the same sign as those which appear in the direct piezoelectric effect when there is compression in the direction of the axis in question. Here also the effect may be divided into two parts, which we may describe as follows, again referring to fig. 15:—

1. Positive charge on the surface  $b l$  and negative charge on the opposite surface, expand the crystal in the direction of the  $X$  axis (longitudinal reciprocal piezoelectric effect).

2. Positive charge on the surface  $b l$  and negative charge on the opposite surface compress the rod in the direction of the  $Y$  axis. (Transverse reciprocal piezoelectric effect.)

The reversal of sign of these charges of course changes expansion into contraction and *vice versa*. The amount  $\delta$  of the expansion or contraction produced by application of a difference of potential  $U$  to the opposite surfaces  $b l$  may be calculated in a way given by Voigt (466). For the longitudinal effect we have the relation  $\delta = d_{11} U$ , and for the transverse effect

the relation  $\delta = d_{12} U \frac{l}{d}$ . Here  $d_{11}$  and  $d_{12}$  are called the piezoelectric moduli.

In the case of quartz  $d_{11} = d_{12} = -6.36 \times 10^{-8}$  cm $^2$ g $^{-1}$ s. In the case of the longitudinal effect, where the mechanical change in the crystal is independent of the dimensions and only dependent on the applied voltage, we get for a tension of 3000 volts in the direction of the  $X$  axis an expansion or contraction of  $6.36 \times 10^{-7}$  cm. On account of this very small effect the direct exhibition of the reciprocal

piezoelectric effect is not easy, and only possible by means of very sensitive mechanical or optical multiplying devices.

Piezoelectric ultrasonic generators are made not only from quartz but from tourmaline, which likewise belongs to the trigonal system. The relationship of this are somewhat simpler than in the case of quartz ; there is only one polar axis which is piezoelectric, and this coincides with the optical axis of the tourmaline. The piezoelectric modulus has the value  $5.78 \times 10^{-8} \text{ cm}^2 \text{g}^{-1} \text{s}$ . Piezoelectric tourmaline plates are therefore cut so that their surfaces are at right angles to the optical axis.

The analogy between piezoelectric phenomena and magnetostriction is at once obvious. The reciprocal piezoelectric effect corresponds to magnetostriiction, and the direct piezoelectric effect to reciprocal magnetostriiction. The connections between the field acting and the mechanical deformation produced, or *vice versa*, are considerably simpler in the case of the piezo effect than in the magnetostriiction phenomena, which are in part very complicated.

**2. The Vibrating Piezo Crystal.** If a piezoelectric quartz plate is put in an alternating electric field in such a position that the direction of the field is in the direction of the piezoelectric axis, for example, by putting a quartz plate between the plates of a condenser (fig. 16) connected to a source of alternating current, the quartz will be compressed in one half of the cycle of the field, and expanded by the same amount in the other half. It will thus be set into elastic oscillations of the same period as the field, and their amplitude will be a maximum when there is resonance between the electric frequency and the natural mechanical frequency of the plate. Cady (106) was the first to produce the resonance oscillations of quartz rods and plates in this way, and gave directions for recognizing this resonance between the electric and mechanical oscillations. On account of the longitudinal and transverse reciprocal piezo effects two varieties of oscillation are possible.

**1. The plate carries out longitudinal elastic vibrations in the *X* direction ; we will call these 'thickness vibrations' of the plate.**

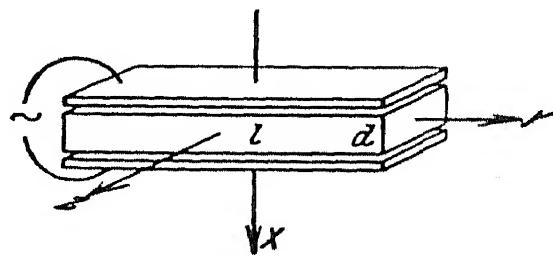


FIG. 16. Position of a quartz rod between the exciting electrodes.

2. The plate is excited to longitudinal elastic vibrations in the  $Y$  direction, which we will call 'length vibrations.'

In the case of thickness vibrations the natural elastic frequency of the fundamental may be calculated, if we leave out of account the influence of the transverse vibrations coupled with it (thus taking the plate as infinitely large), to be

$$N_d = \frac{1}{2d} \sqrt{\frac{c_{11}}{\rho}},$$

where  $d[\text{cm}]$  is the thickness of the plate,  $\rho[\text{g}/\text{cm}^3]$  the density, and  $c_{11}[\text{dyn}/\text{cm}^2]$  a characteristic modulus of elasticity for vibration of this type and direction (34). For quartz  $\rho = 2.65 \text{ g}/\text{cm}^3$  and (according to Voigt)  $c_{11} = 85.46 \times 10^{10} \text{ dyn}/\text{cm}^2 = 8711 \text{ kg}/\text{mm}^2$ . From this we get

$$N_d = \frac{285\ 500}{d} \text{ Hz.}$$

Analogously, we have for the length vibration of a quartz rod (fig. 15) the fundamental frequency

$$N_l = \frac{1}{2l} \sqrt{\frac{E}{\rho}},$$

where  $E = 77.22 \times 10^{10} \text{ dyn}/\text{cm}^2 (= 7871 \text{ kg}/\text{mm}^2)$ . Hence

$$N_l = \frac{272\ 500}{l} \text{ Hz.}$$

The expressions  $N_d d$  and  $N_l l$  are, as we see from the equation, characteristic magnitudes for the respective directions of vibration; they are named vibration coefficients.

In the case of resonance  $N$  is equal to the electrical frequency of the alternating field,  $N_d$  or  $N_l = \nu_{el.} = c/\lambda_{el.}$ , where  $c = 3 \times 10^{10} \text{ cm/s}$ , and  $\lambda_{el.} \text{ cm}$  is the wave-length of the electric oscillation producing the alternating field. This relation combined with the above equation gives the quotients

$$\frac{\lambda_{el.}}{d} \approx 105\ 000 \quad \text{and} \quad \frac{\lambda_{el.}}{l} \approx 110\ 000.$$

For practical reasons  $\lambda_{el.}$  is given in metres, and  $d$  or  $l$  in mm, and we then get the so-called 'wave coefficients,'

$$\frac{\lambda_{el.}^{(m)}}{d^{(mm)}} \approx 105 \quad \frac{\lambda_{el.}^{(m)}}{l^{(mm)}} \approx 110.$$

These simple relations allow us to calculate from the geometrical measurements of quartz plates and rods the wavelengths of the electric oscillations required to set the quartz in mechanical vibration. The equations given are, however, only approximately true, for, in general, bodies of limited size are set in vibration in other directions owing to transverse contraction, and these put the primary frequency out of tune by coupling with it. These matters were investigated in detail for quartz by Giebe and Scheibe (165). Hund (231), as a result of experimental measurements, gives for the fundamental frequency of the thickness vibration of a quartz plate of thickness  $d$  the relation  $N_d = \frac{287 \pm 5}{d}$  kHz, and for a quartz rod of length  $l$  vibrating longitudinally in the  $Y$  direction, the relation  $\frac{278.5 \pm 30}{l}$  kHz.

The sharpness of resonance of quartz vibrating in air is extremely great. The logarithmic damping is of the order of  $10^{-4}$ . The decrement was determined experimentally by Gockel (166) in the case of quartz, tourmaline, Rochelle salt, and some other piezoelectric crystals. These measurements show that the damping increases in general with decrease in the velocity of sound, and is greatly dependent on the condition of the surface of the crystal; varnishing this was already sufficient to increase the damping. Becker (37) made use of a very ingenious method, which we cannot describe further here, to measure the damping of quartz plates in a liquid. On account of the low value of the damping, very exact tuning between the exciting alternating voltage and the natural frequency of the quartz is necessary. On account of this sharpness of tuning, quartz plates vibrating at resonance frequencies are used in high-frequency work as standards of frequency, for controlling transmitters, and as stabilizers for oscillating circuits.

In this book we are interested only in their use as sound generators. Both forms of oscillation are used for this purpose. When a quartz rod is set in longitudinal vibration sound is emitted from the end surfaces of the rod as in the case of magnetostriction vibrators. In the case of thickness oscillation, on the other hand, the sound waves proceed mainly in a direction at right angles to the surface of the plate. Thickness oscillations

are used in general for producing ultrasonics down to a frequency of 200 kHz corresponding to a quartz plate of 13.6 mm thickness. Longer waves are produced by longitudinal oscillations of quartz rods, but it is, however, then no longer possible to radiate the sound from the larger section. In order to get greater sound energy over a large area at lower ultrasonic frequencies, it is possible to avoid the use of the necessarily very thick and expensive quartz plate by using, according to Langevin (285), a number of smaller quartz plates of equal thickness cemented between steel plates, and to set this system vibrating in its natural thickness frequency. The mode of action of steel-quartz oscillators of this sort has been fully investigated by Sokoloff (434, 434 a; see also p. 195).

The upper limit of frequencies attainable by means of piezo-quartz vibrators lies at about 50,000 kHz. The plate cut at right angles to the *X* axis is in this case only 0.054 mm. thick and hence very fragile. Also, the plate may be broken down electrically by a too powerful field and so destroyed. It is possible to go a little further, as was shown in the first instance by Straubel (447), by using tourmaline plates. The elastic modulus of tourmaline in the direction of the piezo axis is  $E = 16.03 \times 10^{11} \text{ dyn/cm}^2$  ( $= 16\ 339 \text{ Kg/mm}^2$ ); the density varies between 2.94 and 3.35. This gives for tourmaline plates of thickness

$$d \text{ cm a natural frequency of } N_d = \frac{363\ 620 \pm 9110}{d} \text{ Hz and}$$

$\lambda_{\text{el}}^{(\text{m})} \approx 82.5d^{(\text{mm})}$ . A tourmaline plate has therefore to be 35 per cent. thicker than a quartz plate for the same natural frequency. Tourmaline plates are made to-day which give frequencies of 150,000 kHz in the fundamental.

In order to attain still higher ultrasonic frequencies with piezo-electric crystal plates, no other course remains but that of producing overtones in plates of a lower natural frequency. The energy output of the plates then becomes less, but on the other hand they may then be excited with considerably greater electric energy without risk of destruction. Particularly for measuring purposes, which in general do not call for particularly high ultrasonic energy, it is very convenient to produce the higher overtones in a plate, with the further advantage, that a number of different frequencies may be produced by a single plate. As Bergmann (45) has shown, the overtones in plates, the surface of

which is large compared with the thickness, follow the harmonic law when set into thickness vibration. Table I gives the measured natural frequencies  $N_k$  of a number of overtones for a quartz plate cut as in fig. 15 and having the dimensions  $l = b = 19.96$  mm, and  $d = 9.9$  mm; the frequencies  $N_k'$  calculated by the harmonic law, and the relative divergence from these values,  $\Delta N = \frac{N_k - N_k'}{N_k}$  are also given.

TABLE I

*Measured ( $N_k$ ) and calculated ( $N_k'$ ) natural frequencies of a piezoelectric quartz plate in thickness vibration.*

$k$	$N_k$ in kHz	$N_k'$ in kHz	$\Delta N$ in %	$k$	$N_k$ in kHz	$N_k'$ in kHz	$\Delta N$ in %
11	3 170	3 170	0.00	81	23 346	23 343	+0.17
21	6 061	6 052	+1.48	91	26 201	26 225	-0.92
31	8 926	8 934	-0.90	101	29 126	29 107	+0.65
41	11 816	11 816	0.00	111	32 051	31 988	+1.97
51	14 713	14 697	+1.09	165	47 544	47 550	-0.13
61	17 585	17 579	+0.34	179	51 546	51 584	+0.74
71	20 422	20 461	-1.91	191	55 046	55 042	+0.07

The deviations from the harmonic law lie within the errors of measurement.

Only the odd overtones can be excited very strongly, a fact which is dependent on the manner of piezoelectric excitation. Fig. 17 shows a section through a quartz in the  $XZ$  plane; the distribution of pressure and the oscillatory motion in the plate are given for vibration in the fundamental as well as in the second and third overtone. The dotted curve in the upper part shows the pressure distribution in the plate for the fundamental, when the electrodes, which are to be taken as at the right and left, are

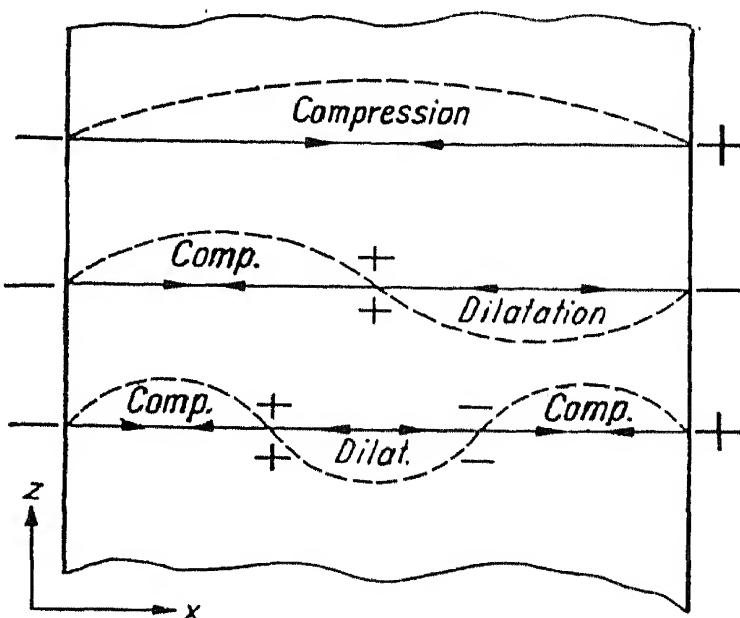


FIG. 17. Pressure and charge distribution in a quartz plate vibrating in the fundamental, and second and third harmonics.

charged with the signs indicated. The arrows show the direction of motion of the parts of the plate. In the middle of the plate we have a compression maximum, which changes to an expansion maximum after half an oscillation, the sign of the charges then being reversed. The case of the second overtone is represented by the second curve. Here we have at the same instant a position of compression and one of expansion ; we see from the signs of

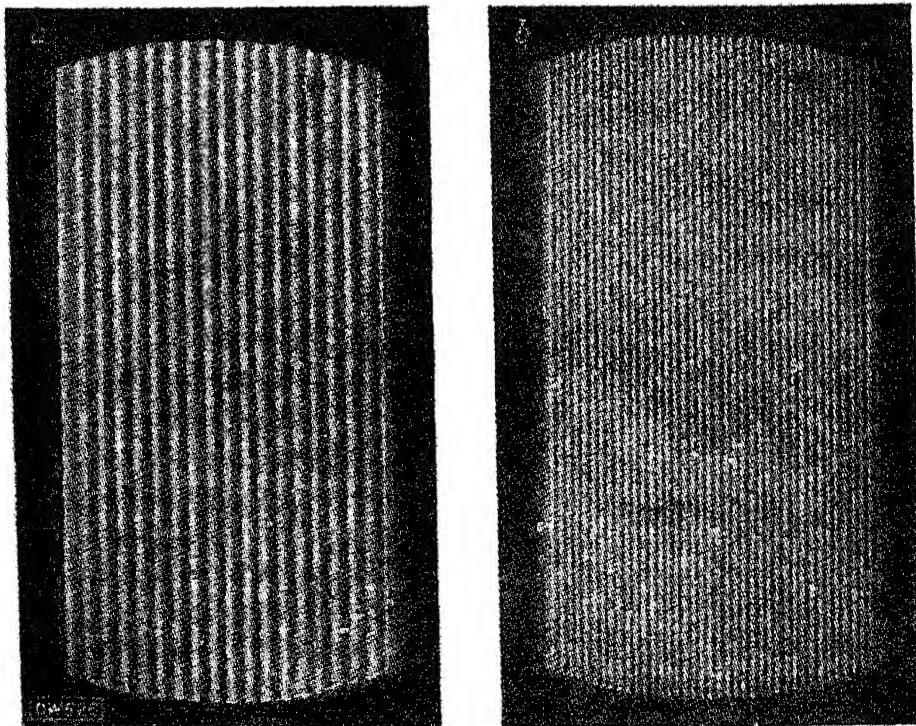


FIG. 18. Distribution of strain in a quartz vibrating in the higher harmonics photographed by the optical striation method. (See page 58.) (a) 19th harmonic, (b) 39th harmonic (Bergmann).

the charges as marked, that in order to bring about this condition equal charges of the same sign must be present on the external electrodes, and in the middle of the plate a charge of opposite sign ; this is a state of affairs which cannot be practically attained in the case of a quartz plate. This is no longer the case as regards the third overtone, which is also shown in the figure. Here a compression and an expansion region neutralize as regards their electric excitation, and oscillation is excited in the remaining compression region. Thus the odd overtones can always be set up, for all charges neutralize one another excepting those at the end of one-half wave. The fact that it is sometimes possible to excite the even overtones of lower numbers by using very strong electric fields depends upon the want of symmetry frequently present in

the quartz plate or in the electric field. Fig. 18 shows the distribution of pressure in the section of a quartz plate vibrating in overtones, made visible by an optical method which will be discussed later on p. 58. Those parts of the oscillating plate where the index of optical refraction is least disturbed—that is to say, the nodes of pressure—remain dark, while the places of maximum compression or expansion are seen bright. In the left-hand photograph we are shown the 19th overtone, in the right-hand the 39th. The electrical frequencies used for excitation were 5510 kHz and 11,450 kHz. Fig. 19 shows a magnified part of a photograph taken by the same optical method of a quartz cube vibrating in the  $X$  direction in the 287th harmonic; the length of its edge was 20 mm. The distance apart of two pressure nodes in this quartz was only 0.07 mm at a frequency  $N = 42,320$  kHz.

It is also possible to produce, in quartz rods, longitudinal elastic oscillations of a higher order in an analogous manner; the various possible forms of electric excitation have been investigated in detail by Giebe and Scheibe (165); the overtones of quartz rods are, however, hardly used for producing ultrasonics, since quartz plates vibrating in their thickness give these frequencies at considerably greater amplitude and also over a larger area.

It is important for the radiation of sound from quartz plates vibrating in thickness that the surfaces of the plates should move to and from one another in a truly parallel manner—that is to say, that they should behave like pistons, and not suffer changes of shape which would produce an uneven distribution of the radiated sound. Unfortunately, investigations of Dye (134), Skellet (429, 430), Osterberg (338, 340), and Straubel (449) have shown that when a quartz plate is in thickness vibration, some parts of the plate surfaces take no part in the motion, while the amplitude of others is very variable. The surface of the plate shows, generally peaking, a more or less complicated Chladni pattern. An

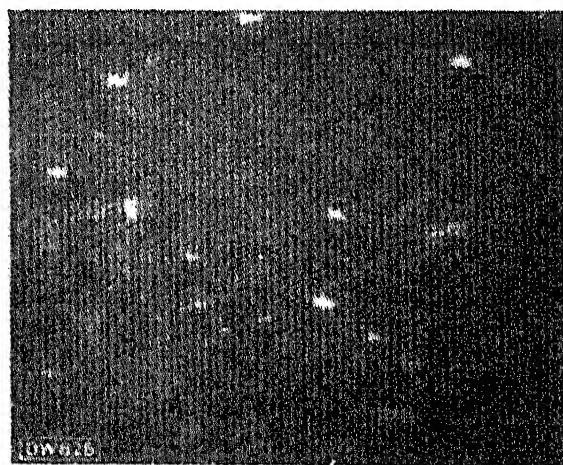


FIG. 19. Part of the striation picture, magnified 8 times, of a quartz cube vibrating in the 287th harmonic (Bergmann; method as in fig. 18).

example of this is given in fig. 20 ; the photographs were taken by Dye using a specially constructed interferometer. A uniform system of interference bands is produced by a plane-glass plate set over the polished quartz surface at a very short distance and slightly inclined to it. If the quartz plate is then set in vibration the interference bands are washed out, if the illumination is steady at the points where the surface is in motion. The right-hand photograph shows clearly that some parts of the plate are com

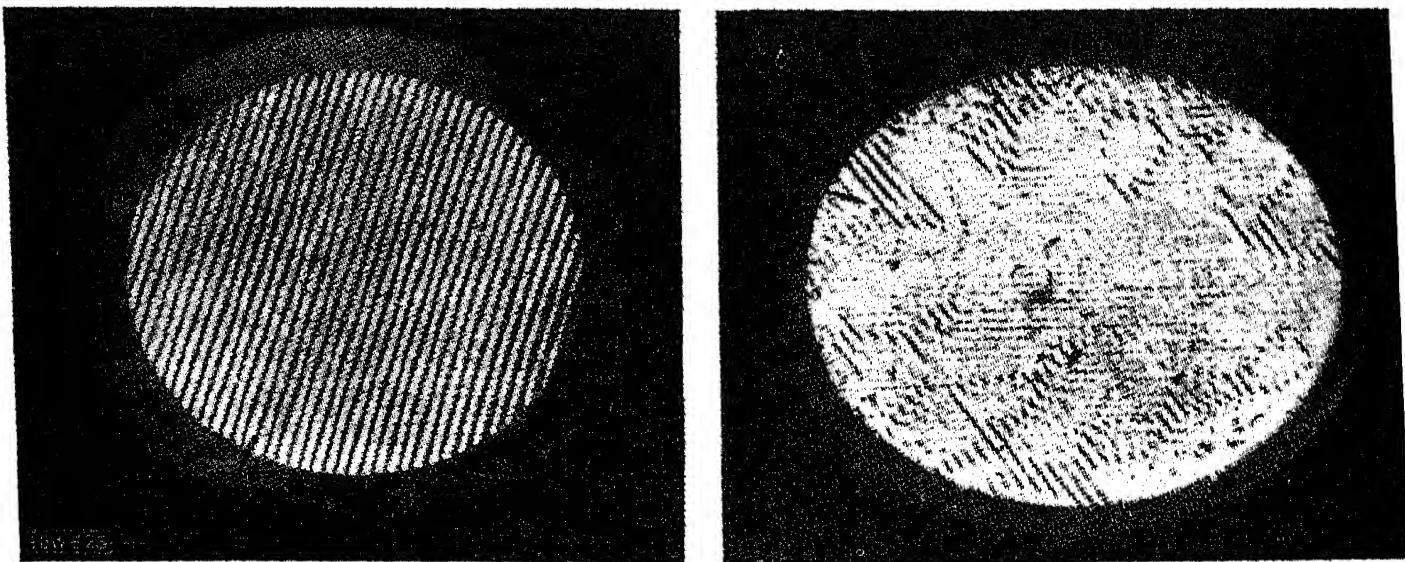


FIG. 20. Interference photographs of the surface of a motionless (a), and a vibrating (b) quartz plate, vibrations being in thickness (Dye).

pletely motionless. In dealing in Chapter II with the optical methods used for investigating the sound waves sent out from a vibrating quartz plate, we shall learn more of a very sensitive method of recognizing those places on the quartz surface which remain at rest, and those radiating sound most strongly.

This uneven motion of the plate surface, which is found also in the case of pieces of quartz perfectly homogeneous optically, is caused in the first place by the production of longitudinal oscillations in the plate on account of its transverse contractions. The irregularity of vibration frequently leads to destruction of the plate, for the elastic limit of the plate may be easily over-stepped in places of strong vibration, even when the load on the whole plate is relatively small. In addition, the modulus of elasticity  $E$  of the quartz in the  $YZ$  plane is not a constant, so that the natural frequencies of the longitudinal vibrations of a plate in different directions are very different. In this way, slight detuning may suddenly set quite different parts of the plate vibrating powerfully.

In fig. 21, the values of the elastic modulus of quartz in  $\text{kg}/\text{mm}^2$  are shown in polar co-ordinates for the  $WZ$  plane. The modulus has a maximum value for an angle of  $-48^\circ 19'$ , and a minimum for an angle  $+71^\circ 32'$ , the maximum value being 13,050 and the minimum 7060  $\text{kg}/\text{mm}^2$ . Experiments showed that a quartz plate is set in elastic vibrations in just these two directions in which the modulus has its extreme value. Quartz rods also, cut in the direction of fig. 15 and set in longitudinal vibration, never vibrate exactly in the direction of the  $Y$  axis, according to Straubel (448). The line of the node of motion of a quartz rod, cut in this way (the  $90^\circ$  cut as it is called), is shown in fig. 22A by the use of

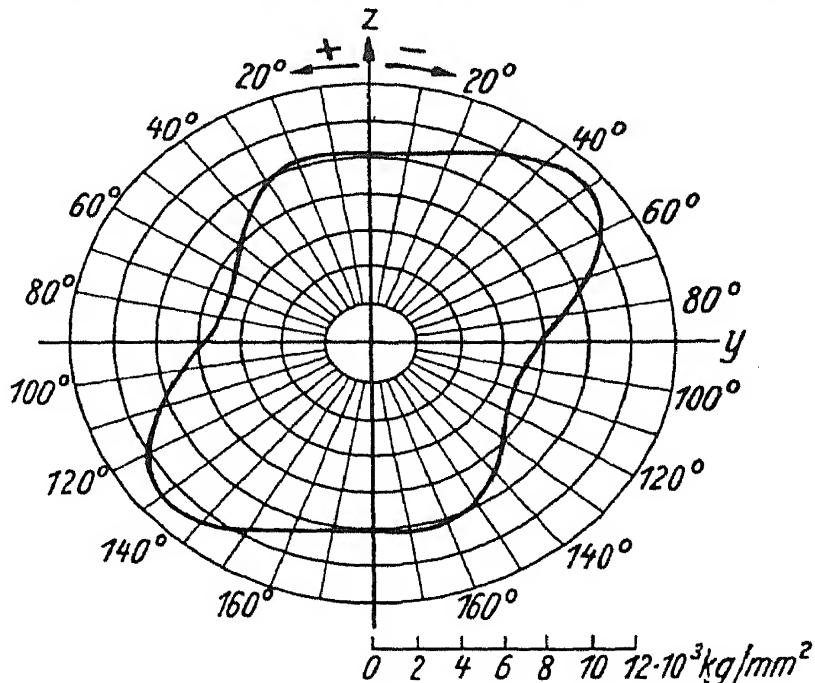


FIG. 21. Intersection of the elasticity surface of quartz with the  $YZ$  plane.

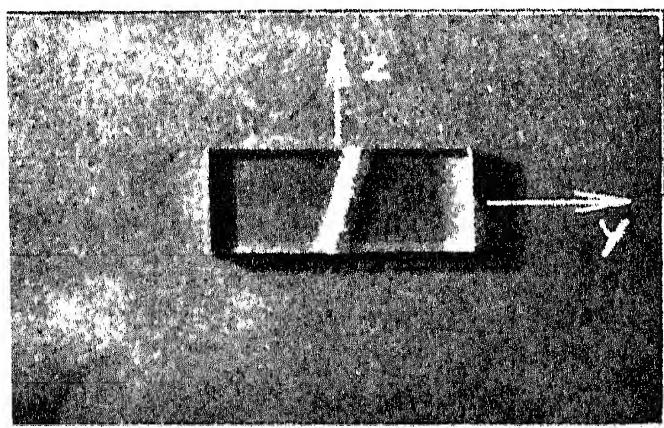


FIG. 22A. Node line of a normally cut quartz rod vibrating in the  $Y$  direction (Straubel).

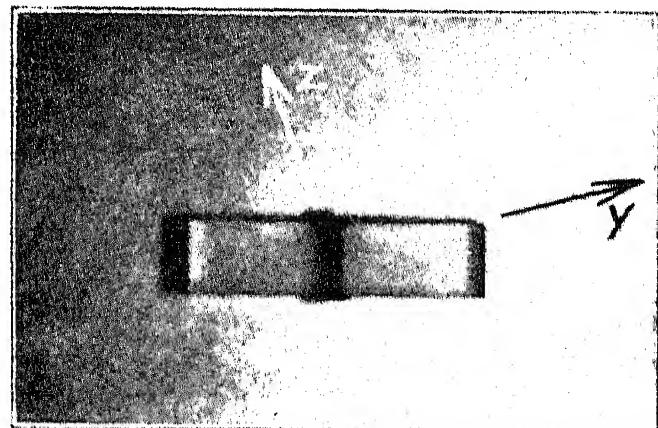


FIG. 22B. Node line of a vibrating quartz rod orientated at  $71^\circ$  (Straubel).

lycopodium powder. As we see, this nodal line is inclined at an angle of about  $13^\circ$  to the  $Z$  axis, and thus indicates that the rod is vibrating in the direction of the smallest modulus of elasticity. But if the longest axis of the rod coincides with the minimum of the modulus ("71° cut," or "single-wave quartz"; orientation

as in fig. 23), the vibrations then follow exactly the geometrical form of the rod, as may be seen from the nodal line of fig. 22B.

Bücks and Müller (105) measured microscopically the amplitudes of vibration of quartz rods with  $90^\circ$  and  $71^\circ$  orientation over the ends ; fig. 24 shows the amplitudes of vibration over the end faces of the two specimens, the direction of excitation being at right angles to the paper. We recognize at once that only the  $71^\circ$  quartz vibrates like a piston. The amplitude was found by

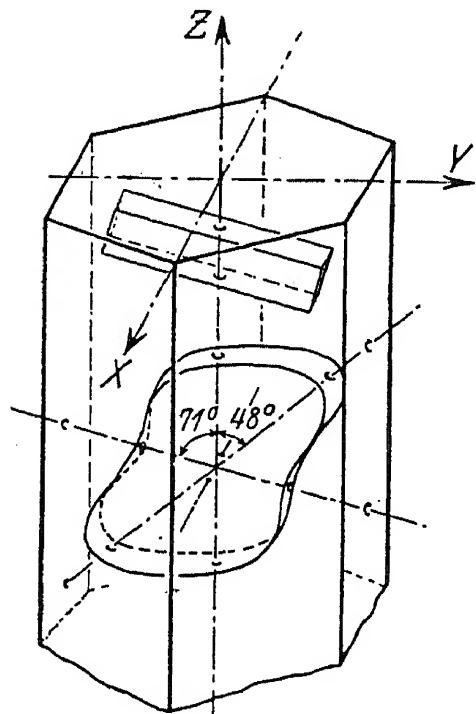


FIG. 23. Cutting of quartz rods and plates with  $71^\circ$  orientation (Straubel).

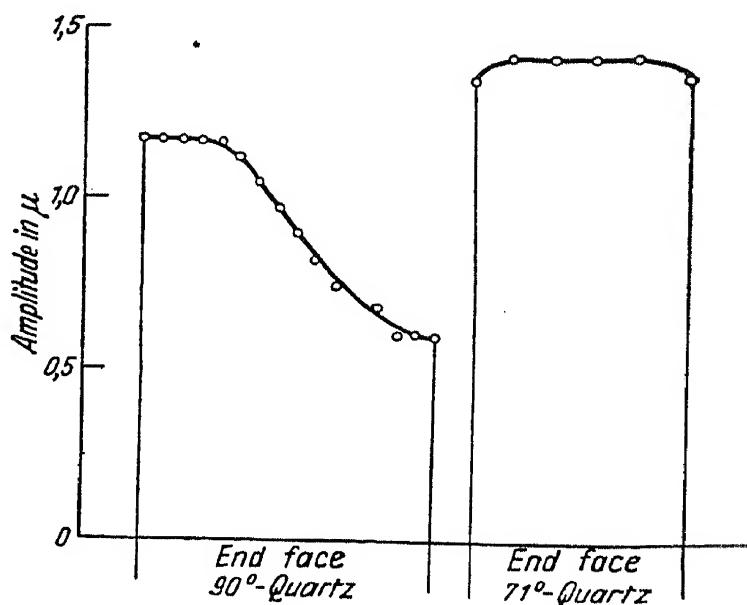


FIG. 24. Amplitude of vibration of the end surfaces of quartz rods.

Bücks and Müller to have the value  $1.5 \times 10^{-3}$  mm ; this result agrees with measurements by Osterberg (339), who also determined the amplitude vibration of piezoquartz plates by means of interferometer photographs.

Straubel (448) gave quartz plates, cut with their surfaces at right angles to the  $X$  axis, such shapes that the edge at every point was at a distance from the middle of the plate proportional to the square root of the elastic modulus in that particular direction. Fig. 25 shows the shape of such plates ; their orientation with respect to the quartz crystal may be seen from fig. 23, which, however, only gives the position of the plate, but not its exact shape. The edge of the plate in fig. 25 is obtained by putting in the polar diagram of fig. 21 the values of  $\sqrt{E}$  instead of  $E$ .

The effect of this is to give all transverse oscillations the same frequency, and so cause the plate when vibrating in thickness to exhibit much more uniform motion of its surfaces. Although even here the ideal case of a piston vibration is not realized completely, plates of this sort will stand considerably higher loads.

Other orientations and directions of cut for piezoelectric quartz plates and rods have recently been suggested from various sides (31, 271, 281, 282, 319, 320), the need having arisen for quartz oscillators with the lowest possible temperature coefficient. The temperature effect is conditioned by the thermal expansion, and the dependence of the elastic modulus on temperature. The temperature coefficient  $\frac{1}{N} \frac{dN}{dT}$  is of the order of  $50 \times 10^{-6}$ .

The sign of it differs for the various forms of vibration, thickness and longitudinal. There are certain favourable orientations of quartz plates at which the temperature coefficient is zero or a minimum. Bechmann (34, 35) has shown that these orientations may be calculated from the general constants of quartz. This fact is of the greatest importance in the use of piezoquartz for the regulation of high-frequency transmitters, for here the greatest possible constancy of frequency is necessary. In the use of quartz for the production of ultrasonics, this question plays a smaller part. Generally speaking, the frequency used in exciting quartz for ultrasonic work will be measured and continuously controlled by means of an electric wave-meter. It is then only necessary to make certain that the frequency of the electric circuit does not change sensibly in the course of the investigations. But when ultrasonics of considerable energy are generated, the large amplitudes of the quartz and the unavoidable electric losses always cause such large rises of temperature, that one has to reckon with a certain change in frequency, a matter of minor importance in most investigations of this sort.

In conclusion we may mention a form for piezoelectric quartz described by Gruetzmacher (176), which makes it possible to bring the ultrasonic waves proceeding from a vibrating quartz surface to a focus, and get there a much increased intensity of

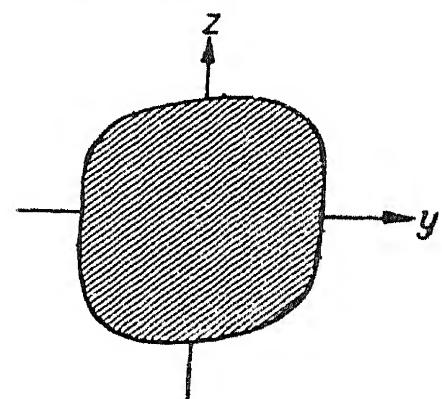


FIG. 25. Quartz oscillator in disc form with edge proportional to square root of elastic modulus (Straubel).

ultrasonic effect. The quartz is formed for this purpose like a spherical concave mirror (fig. 26). The orientation with respect to the crystal is shown by fig. 27 (a) and (b). The form (a) has one of the electric axes  $X_1$ ,  $X_2$ , and  $X_3$  at right angles to the middle of the spherical surface, while in (b) the plane containing  $X_3$  and the optical axis at right angles to the paper is tangential to the sphere. When the quartz is set in vibration in the direction of its thickness, the rays of sound are emitted from the vibrating surface

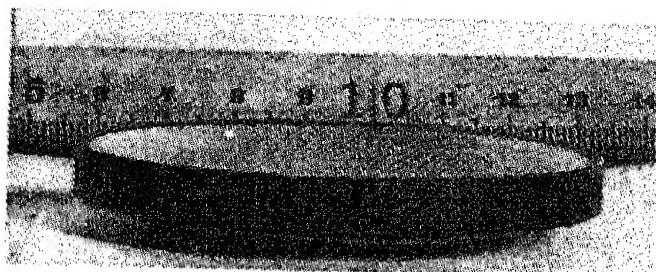


FIG. 26. Concave piezoelectric quartz (Gruetzmacher).

in a direction mainly at right angles, and so meet at the concave side of the bowl in a focus  $P$ , which is at the centre of curvature of the bowl. The effect of this is to increase to an extraordinary degree the energy at the focus, the increase amounting to as much as 150 times the energy of a small surface element

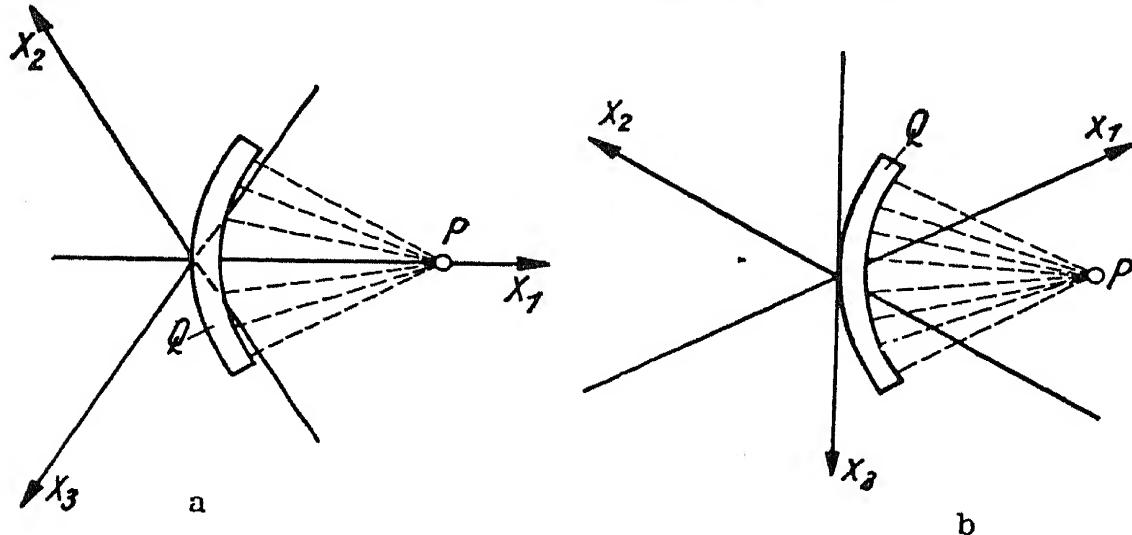


FIG. 27. Manner of cutting the quartz of fig. 26 from the crystal to give ultrasonic focus.

close to the vibrating crystal. The effect of this is that such a crystal with a focus enables very great ultrasonic amplitudes to be attained by exciting it only weakly, and thus avoiding the danger of destroying it by overloading in excess of the elastic limit.

**3. The Construction of the Piezoelectric Ultrasonic Generator.** Piezoelectric crystals are most conveniently set in vibration by the aid of undamped electric oscillations, which may be generated

without difficulty by means of valves at any desired frequency and intensity. The connection between the quartz and the electric generator may be made in various ways. The simplest consists in putting it in parallel with the capacity of the oscillating circuit as in fig. 28). The oscillator circuit is here the well-known one of Hartley. The oscillating circuit, made up of a self-induction and variable condenser is tuned to the natural frequency of the quartz  $Q$  by varying the capacity. This type of connection for the quartz is always used when powerful vibrations, particularly in liquids or solids, are to be generated. Since the reciprocal

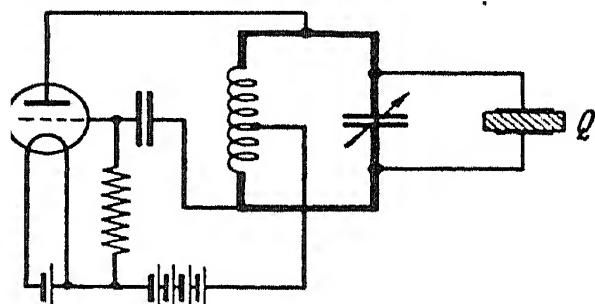


FIG. 28. Circuit of a valve oscillator of Hartley type, and its connections to the piezoquartz.

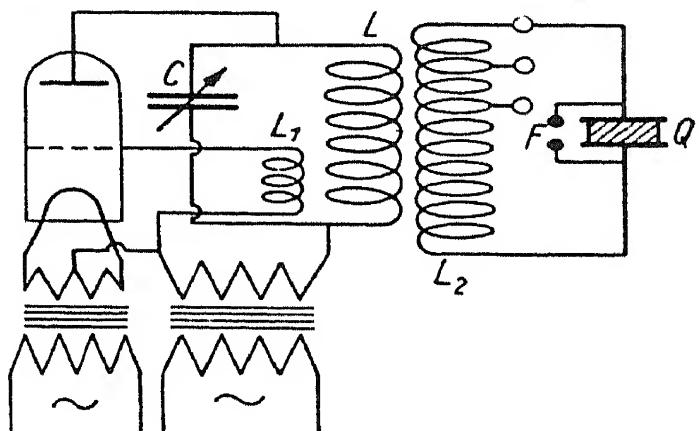


FIG. 29. Circuit of a retroactively coupled valve generator driven from the alternating mains, and driving a piezoquartz by inductive connection.

piezoelectric effect, and hence the amplitude of vibration of the quartz, is proportional to the voltage applied to it, it is frequently useful to transform up the alternating voltage produced by the oscillator, say by means of a Tesla transformer, as shown in fig. 29 for a retroactively coupled oscillator.  $L$  is the inductance of the oscillator circuit,  $L_1$  the reaction coil, and  $L_2$  the Tesla coil inductively coupled with the oscillator inductance and provided with tappings so that it may be adjusted to a suitable value with reference to the capacity of the quartz. To avoid sparking at the quartz  $Q$  a safety spark gap  $F$  is put in parallel with it. In this circuit the generator is operated from the alternating current main, one phase only being used for the anode current. It is naturally preferable for energy reasons to put a steady direct voltage on the anode, and this may be obtained from a direct current machine or from the alternating mains by means of a rectifier. For smaller voltages, dry rectifiers may be used, while the use of diodes is necessary for higher voltages. The energy

given to the quartz may, when it is inductively coupled, be adjusted by varying the coupling, or when metallically connected, by putting a small variable condenser in the connection to one of the two quartz electrodes. Experience in building a two

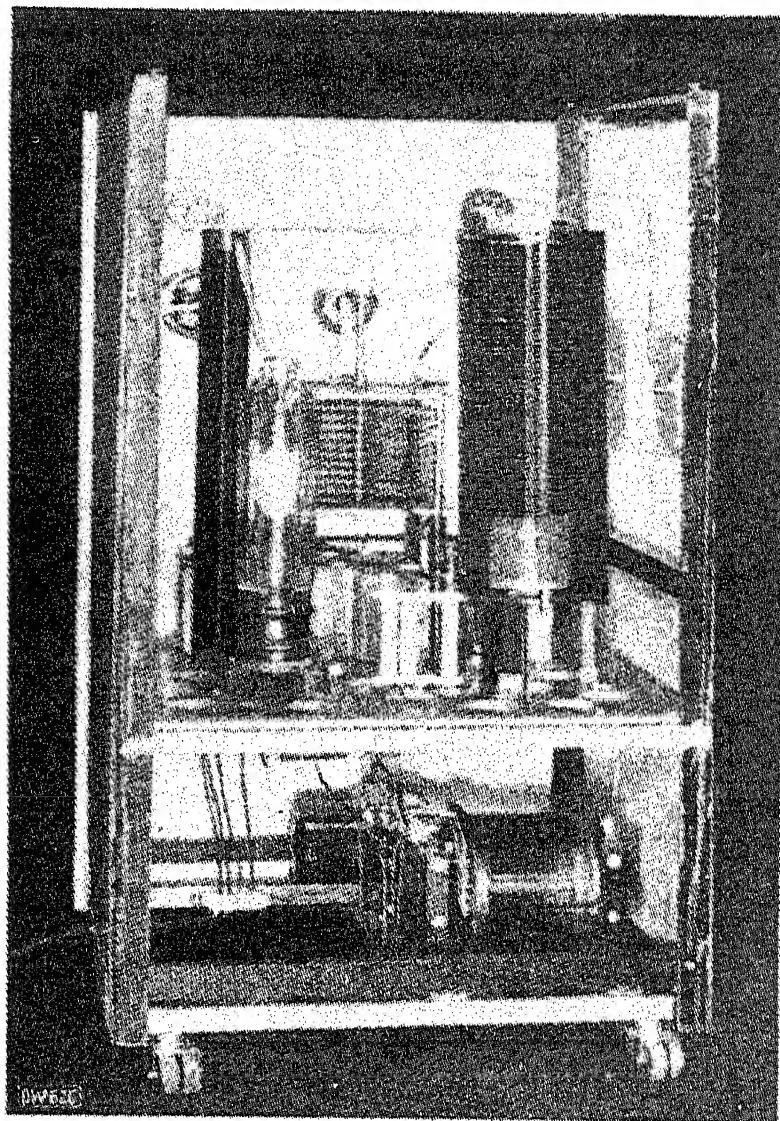


FIG. 30. View inside a valve oscillator for ultrasonics made by the firm of Siemens-Reiniger-Veifa.

*KW* valve generator for ultrasonics is given in a paper by Ardenne (6 a).

Figs. 30 and 31 show a valve generator for ultrasonics in a general view, and open to show the construction ; this is built by Siemens-Reiniger-Werke A.G. The output of this generator, which is worked directly from the main, is about 350 watts at a wave-length of 800 metres.

Fig. 32 gives the circuit of a small valve generator with an output of about 5 to 12 watts, which has proved valuable for ultrasonic work in the range from 7 to  $3 \times 10^4$  kHz. The valve

sed in this tube is the small Telefunken RS 241. The anode voltage  $E_a$  for this valve is 300 volts, the filament voltage  $E_h$  is

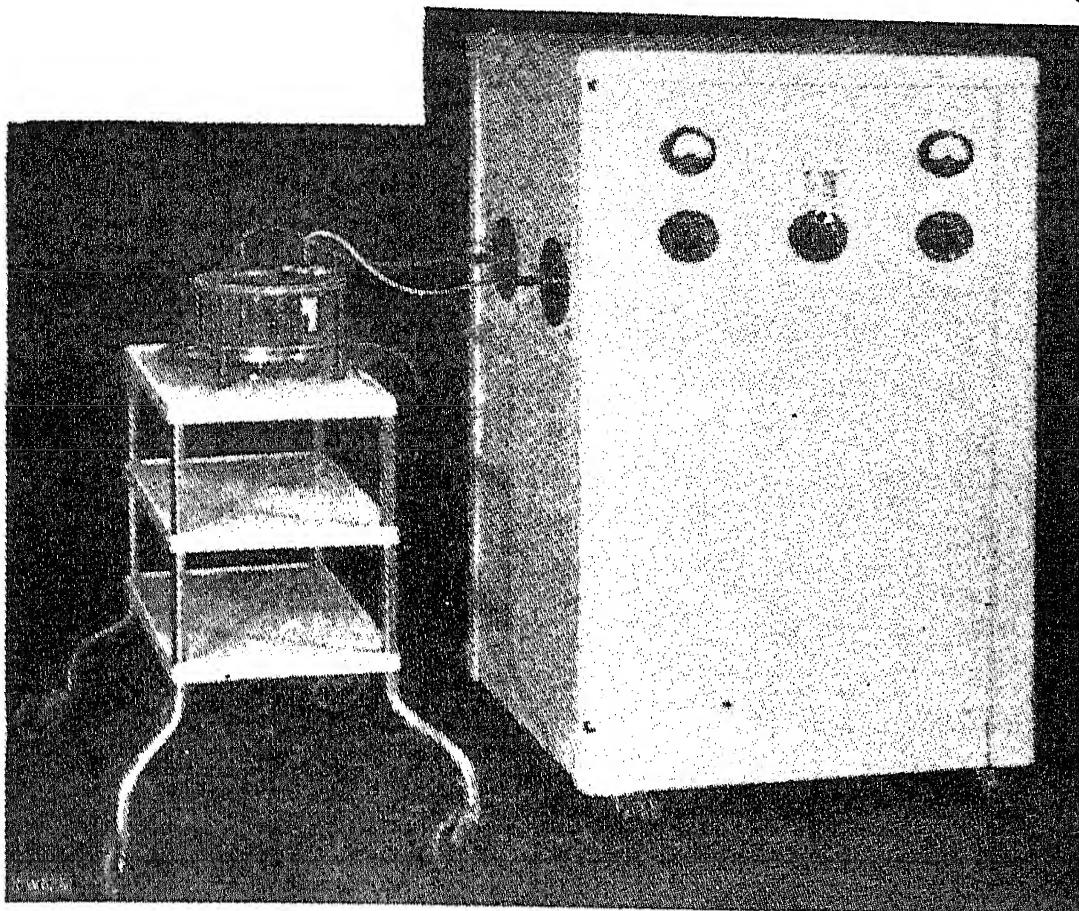


FIG. 31. Ultrasonic generator, general view.

8 volts, and the filament current 0.65 ampere. The oscillator of the Hartley type, which is very convenient for a quick change

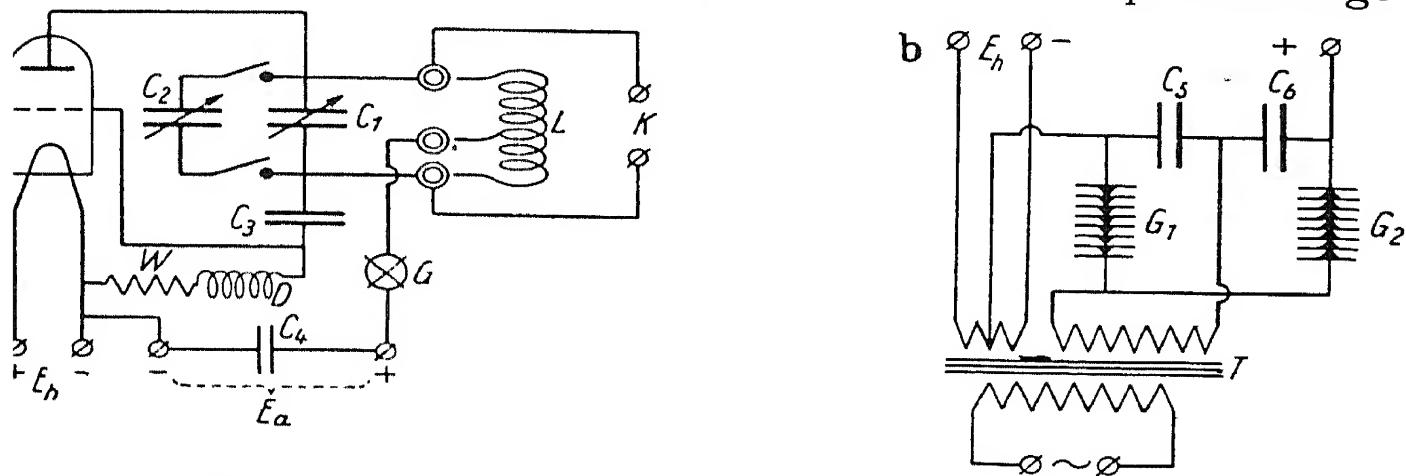


FIG. 32. Circuit of a valve oscillator and mains unit.

wave-length, since it is then only necessary to change the inductance with its three tappings. In Table II the dimensions of the inductances needed for 11 to 4000 metres are given.

TABLE II

*Data of Inductances of a Valve Oscillator for Wave-lengths 11 to 4000 m*

Wave-length	Number of Turns		Coil Diameter in mm	Pitch of Winding in mm	Construction
	Whole Coil	Between Grid and Filament			
11 to 21 m	2	1/3	110	8	
16 " 32 m	4	1·1/2	80	4	
30 " 60 m	9	3	80	4	
55 " 110 m	14	5	100	2	
100 " 170 m	24	9	100	2	
250 " 750 m *					
140 " 300 m	41	14	100	1·7	
550 " 2200 m *					
1100 " 4000 m *	90	30	150	1·2	Three layers on pertinax tube wound free from capacity.

The variable condenser  $C$  has a maximum capacity of 100 cm and must have a fine adjustment. In the case of the sizes marked with an asterisk in Table II, a second variable condenser  $C_2$  with a maximum capacity of 2500 cm must be put in parallel with  $C_1$ . The condenser  $C_1$  then serves for fine adjustment. The grid blocking condenser  $C_3$  has a capacity of about 1000 cm.  $D$  is a choke,  $W$  a variable grid leak of 15,000 to 20,000 ohms, and  $C_4$  a blocking condenser of 1 to 2 mf. The two terminals  $K$  serve for connecting to the quartz resonator,  $G$  is a glow lamp of 15 to 25 watts inserted in the anode circuit, serving as an automatic protection for the valve by lowering the anode voltage by the drop on it when the anode current gets too great.

When the oscillator is to be driven from mains, a set may be used such as that given in the circuit diagram 32 (b). The transformer  $T$  gives, in addition to the filament voltage, an alternating voltage of half the value of the required direct voltage; the two dry selenium rectifiers  $G_1$  and  $G_2$  rectify both phases and deliver the current to the condensers  $C_5$  and  $C_6$  connected in series. For reasons of symmetry, the negative pole of the direct volts is connected with the middle of the filament transformer winding.

The direct connection of the piezoquartz with the high-frequency generator, which we have just described, is named the

resonator circuit.' The quartz is set into forced oscillation by the alternating electric field. This form of excitation will always be of advantage when powerful vibrations are required. There is in use another method of ultrasonic generation by piezoelectric crystals, the principle of which was given by Cady (106), and later by Pierce.

The piezo crystal in this case works as an oscillator and controls the valve at its own frequency, the valve then supplying the necessary alternating field for maintaining the crystal vibrations. Fig. 33

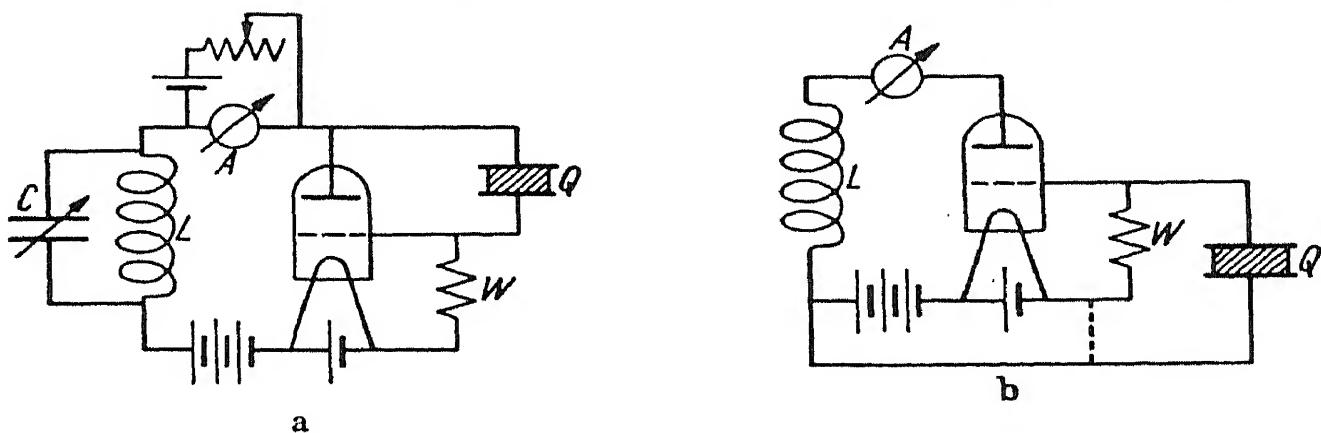


FIG. 33. Pierce's oscillator circuits.

shows the oscillator circuits devised by Pierce and most frequently used. The quartz  $Q$  is connected in form (a) between the grid and anode of the valve, and in form (b) between the grid and the positive pole of the anode battery, or, as shown dotted, directly between grid and filament of the tube.  $W$  is a variable grid leak of the order of 1 megohm;  $L$  is an inductance, in place of which it is also possible to use a coil  $L$  and capacity  $C$ , forming an oscillating circuit, as shown in fig. 33 (a). The milliammeter  $A$  serves to indicate changes in the intensity of vibration of the quartz which may come about, for example, as we shall see later, by action of the sound waves on the quartz. In order to detect very small changes of current a highly sensitive instrument may be used, the steady anode current being compensated by means of a battery and resistance (see fig. 33 (a)). If the quartz is set in natural vibration by any disturbance, such as switching on, the mechanical deformation causes alternating voltages to appear at its electrodes owing to the direct piezoelectric effect, and these acting on the grid of the valve control the anode current with the correct periodicity, so that the quartz is set in stronger vibration. A stationary condition of vibration is then set up, and the frequency

of vibration, and therefore the frequency of the ultrasonics emitted, is then determined only by the quartz. A necessary condition for the production of vibrations is that the anode resistance should be inductive.

When a tuning circuit is used in the anode connection, it must be put out of tune with the crystal frequency (by making  $C$  smaller) as otherwise it has an influence on the latter. These oscillator circuits can only be used for generation of ultrasonics in air and in gases, where the crystal is able to vibrate without damping; they are not suitable for generating waves in liquids, since the powerful damping of the crystal by the liquid stops the reaction. Even in gases the formation of standing waves may sometimes lead to their reaction on the quartz being strong enough to stop oscillation.

The generation of powerful ultrasonics of constant frequency is further possible, in a circuit excited by resonance with the quartz used for generation, by using as regulator a second quartz tuned to the same frequency. In the case of large outputs, this regulation will be done through an intermediate valve; in order to get the two quartz vibrators exactly in tune it is advantageous to use the regulating quartz in a 'vario-holder,' that is, between an adjustable pair of electrodes, whereby its natural frequency may be changed over a range of about two parts in a thousand by changing the distance of one electrode from the surface of the quartz.

Good vibration of the quartz and high efficiency in ultrasonic output call for special attention to the correct placing of the electrodes and a suitable support for the quartz. Quartz surfaces at right angles to the  $X$  axis in which the electric force acts should be given as fine a matt surface as possible, and preferably be covered with a metallically conducting coating. This may be produced either by chemical silvering or gilding, or by evaporating these metals in a vacuum by heat or by cathode sputtering. It is necessary to get the deposit uniform, it may afterwards be thickened by electroplating.

In generating ultrasonics in gases in a vertical direction, it is sufficient to lay the quartz plates with their metallized surfaces on a plane surface. The current may be lead to the upper electrode by a light narrow ring of brass which is pressed gently against the quartz surface by two springs which carry the current.

is often sufficient to use as second electrode a flat metal surface few tenths of a millimetre thick over the surface of the quartz ; has in the middle an opening through which the waves are able to pass. Fig. 34 shows a holder for a rectangular quartz plate suitable for generating a horizontal wave in a liquid. The quartz is pressed by means of an insulated metal spring, serving as the lead for the current, against a flat brass plate. Two small ivory pegs prevent the quartz from slipping down. A holder

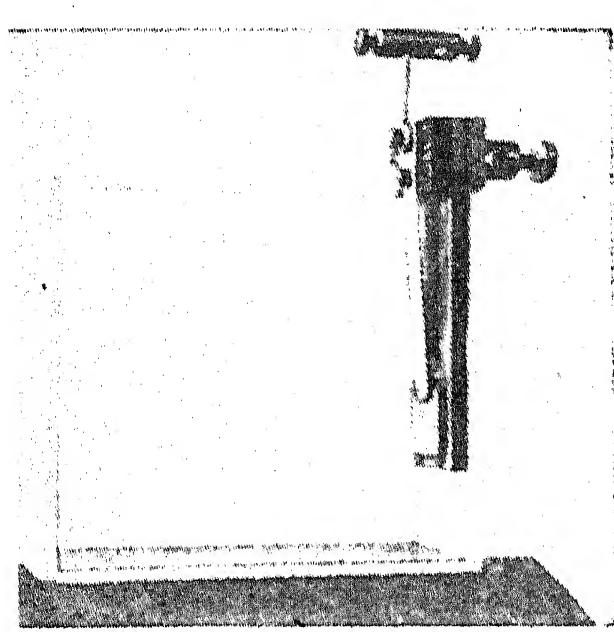


FIG. 34. Fixing of quartz plate in trough of liquid.

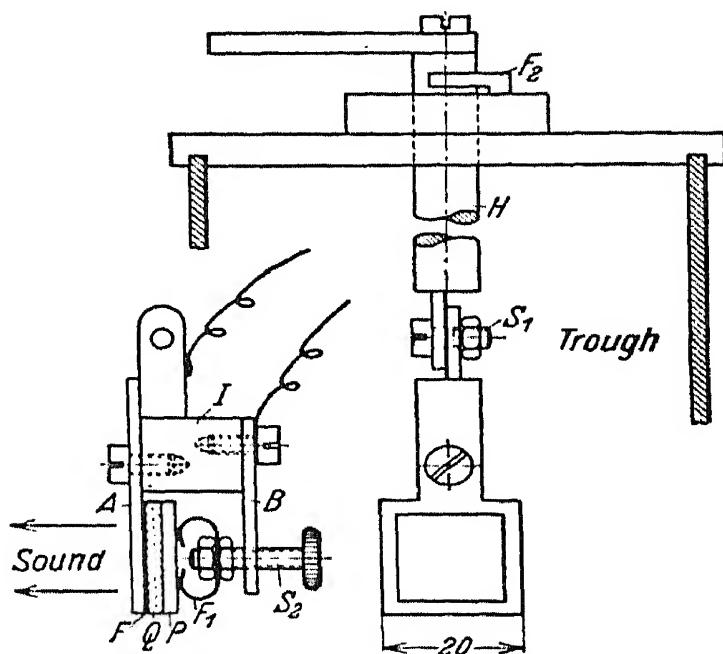


FIG. 35. Bez-Bardili's holder for quartz crystal.

in this form, complete with quartz, is easily put into any glass trough. Fig. 35 shows a quartz holder described by Bez-Bardili (56), which has the advantage of allowing the quartz to be set in any direction in the liquid. A rod  $H$  of insulating material (such as horn, ivory, or other substance not soluble in organic liquids) is mounted so that it can be turned and moved up and down ; it is held by a spring  $F_2$ , and has at the lower end a joint  $S_1$ , carrying the insulating piece  $I$ , to which the two brass plates  $A$  and  $B$  are fixed.  $A$  is in the form of a frame, and  $B$  carries a screw  $S_2$  with a spring  $F_1$  at its end. This passes the quartz  $Q$  through an intermediate flat metal plate  $P$  and a thin metal foil  $F$  against the front frame, through the opening of which the waves escape.

When quartz plates are mounted in this way on a solid base, the vibrations, according to Becker (36), are no longer harmonic,

but acquire an anharmonic character, which results in strong unsymmetry and in a shift in the resonance curve of the quartz vibration. Curve 1 of fig. 36 shows such a resonance curve, in which the relative change of frequency is plotted as abscissa, and the square of the amplitude of vibration  $A$  as ordinate. This anharmonic behaviour of the vibration is caused by the quartz knocking against the fixed base. If, on the other hand, the quartz is hung up free, this phenomenon disappears and its

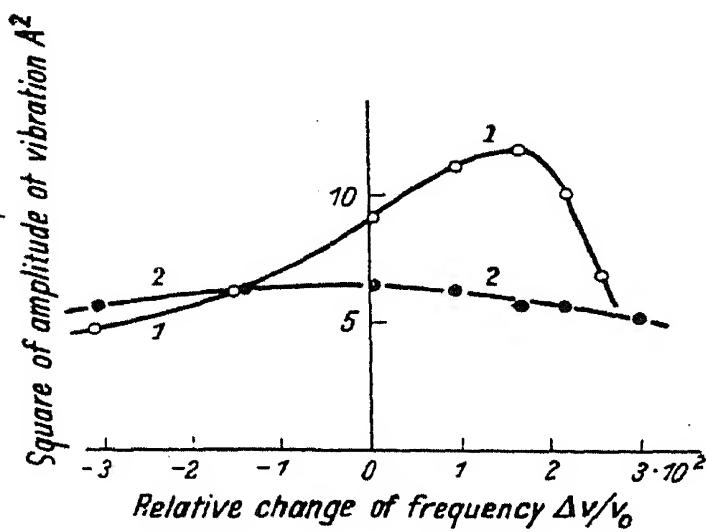


FIG. 36. Resonance curves of a vibrating quartz: (1) on fixed base, (2) hanging free.

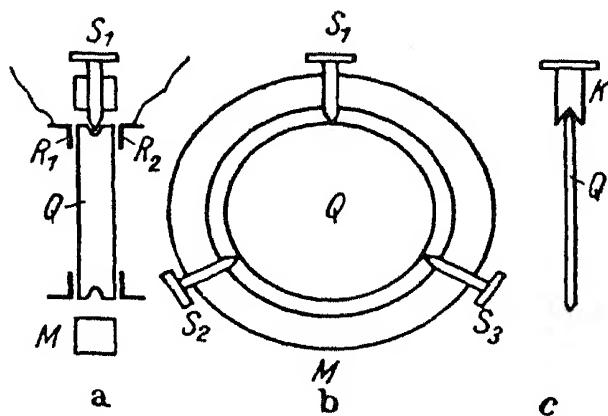


FIG. 37. Free mount for quartz plate.

oscillation is truly harmonic (curve 2 of fig. 36). In this case, however, the damping of the quartz plate becomes considerably greater, since a plate vibrating at both ends freely radiates waves in two directions. Further details must be sought in the original paper of Becker. Quartz plates may be given a free support in a way suggested by Bechmann (33), by cutting in the edge of the round plate a groove lying in the nodal plane of thickness vibration. As fig. 37 shows in two sections *a* and *b* at right angles to one another, the quartz plate *Q* may be held by three pointed screws *S*<sub>1</sub>, *S*<sub>2</sub>, *S*<sub>3</sub> in a ring *M*, in such a way that it is able to vibrate freely on two sides. The voltage is brought to it either by two thin strips of aluminium foil, or capacitatively by two metal rings *R*<sub>1</sub>, *R*<sub>2</sub> placed at a short distance from the surface. Very thin quartz plates, in the edge of which it is not possible to put a groove, may be held in a similar way by three pegs with notches in the ends (fig. 37 (*c*)). A similar type of free mount is also advantageous for quartz rods set in longitudinal

bration, in order to assure a safe and reproducible fixing. Fig. 38 shows a holder of this sort; the quartz is clamped between the two metal electrodes in its nodal plane by means of two screws.

Special care is necessary in mounting the large quartz plates used for generating very intense ultrasonics in liquids. Such quartzes are usually either circular with a diameter of 60 to 100 mm, or have the Straubel con-ur. Their thickness varies between 5 and 20 mm, corresponding to a frequency range in thickness vibration of 714 to 142 kHz. Large plates may be loaded under oil for a short time with an H.F. energy of 3 kilowatts. This corresponds to some thousands of alternating volts at the plate electrodes, and hence care must be taken that the insulation is the best possible. These plates can only be driven under paraffin or transformer oil. Experience with the mounting of such plates was first given by Wood and Loomis (5) and later by Freundlich, Söllner and Rogowski (153), and laus (115). The quartzes are best laid upon a bed of lead several centimetres thick, the surface of which is to be made duly plane. Other metals, especially those harder and more elastic, as iron or steel, have been found to be less advantageous; sometimes the quartz vibrations are strongly damped by the communication of vibration to the metal plate; the quartzes sometimes even crack when the bed is too rigid. It is important that the quartz should be bedded down flat on the lead plate, and that there should be no air between the two, but preferably a thin layer of oil free from bubbles. If the second surface of the quartz is metallized, the current is best led to it by a ring of brass, the outer diameter of which should be a few millimetres smaller than that of the quartz surface, in order to avoid the passage of sparks between the upper and lower electrode. It is also advisable for the same purpose not to carry the metallizing of the quartz surface right up to its edge. The upper electrode is either pressed lightly against the quartz by two or

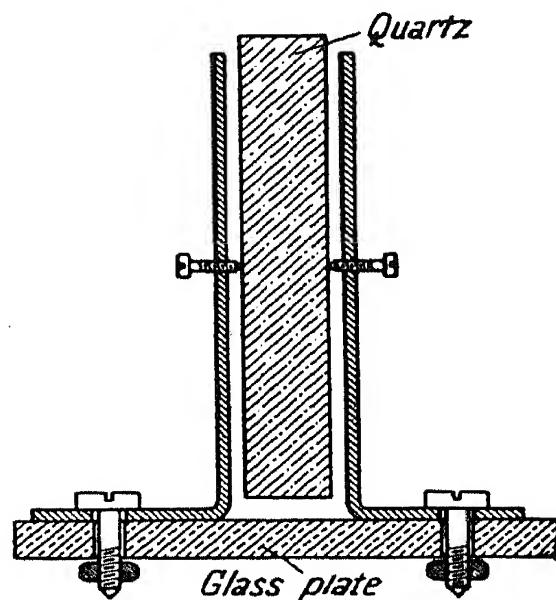


FIG. 38. Holder for piezo-quartz rod.

three springs, which at the same time carry the current, or held and pressed down by four glass hooks pulled down by spiral springs (fig. 39; made by Radio-Loewe, Berlin). The glass hooks also prevent the quartz sliding on the metal bed. Freundlich, Söllner, and Rogowski (153) recommend the use of polished quartz plates, since these in general adsorb less gas and there is less chance of electric breakdown. In this case the most favourable size for the upper electrode must be found by experience.

Rings with too small an inner diameter give a low ultrasonic output, whereas, on the other hand, narrow rings, with too large an opening, lead to irregular electrical excitation of the quartz. It is best to set vibration up gradually, by slowly raising the input of high-frequency energy. Since the quartz is always excited under oil, the maximum effect

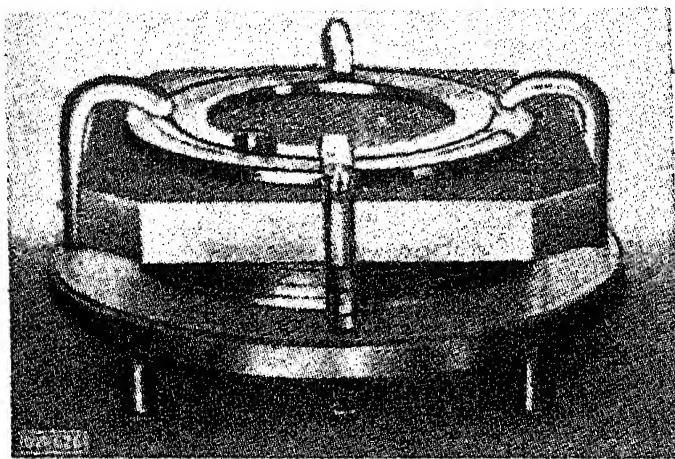


FIG. 39. Fixing of quartz plate for large sound energies (construction of Radio-Loewe, Berlin).

may be recognized by the appearance of an oil fountain on the surface of the oil, which at maximum vibration frequently reaches a height of several centimetres. This is caused by the ultrasonic radiation pressure on the oil surface. When in strong vibration, the quartz gradually heats up, the more rapidly the higher the frequency. Since crystallized quartz is very sensitive to temperature irregularities, it is necessary either to stop working from time to time, or to arrange for very good cooling of the oil. We will return to this point later in discussing ultrasonic equipment.

When the quartz is laid on a solid bed, as so far described, a certain fraction of the energy of vibration is lost by radiation into the supports. This drawback may be avoided, according to Gruetzmacher (177), by bringing only one surface of the quartz in contact with the sound-conducting medium (oil), and having the other in contact with a medium of very small acoustic impedance, for example air, which has the same practical effect as if no sound conductor were present. Fig. 40 shows a suitable arrangement for this purpose. The quartz crystal  $Q$  rests upon

metallic box  $G$ , open at the top, fitting so closely that no oil is able to get in. This results in an almost complete reflection of the sound waves at the lower side of the quartz plate ; they are automatically into the right phase with those radiated upwards and almost double their energy. The total damping of the crystal becomes less, owing to the decrease in the radiation increment ; if the energy of excitation is kept constant the amplitude of vibration of the quartz is increased when it is supported on the box. Oyama (341) and Dognon and Incani (129) also describe a similar arrangement for generating high-intensity ultrasonics.

We may close this chapter with a few words about the ultrasonic energy attainable by means of quartz plates vibrating at high frequency.

Since this depends on the perfection and regularity of the quartz used, as well as upon its mounting, only rough figures for the order of magnitude can be given. Freundlich, Illner, and Rogowski (153) obtained, using plates 60 to 70 mm diameter by 10 mm thick, and a high-frequency voltage of about 34,000 volts, approximately 300 watts ultrasonic energy ; it means, therefore, that the quartz plate radiated an ultrasonic energy of about 10 watts per square centimetre of its surface. Salay (454) arrived at similar values when using a smaller quartz plate  $35 \times 35 \times 4$  mm in size. In this case the height of the oil fountain produced on the oil surface by the ultrasonics mounted to 7 to 8 cm. The sound energy was measured in both cases calorimetrically, by letting the quartz vibrate for some minutes in the oil bath, and determining the rise of temperature caused.

Since the sound waves are almost completely reflected at the surface of the oil, their energy is transformed entirely into heat. If the oil bath is then warmed up in the same time from the same initial to the same final temperature by an electric heater, the energy supplied may be measured, and the ultrasonic energy radiated from the quartz determined approximately.

In these measurements, and in measurements of ultrasonic intensity, radiation pressure, and so on, it is important to control the constancy of the quartz vibrations. This may be done in two

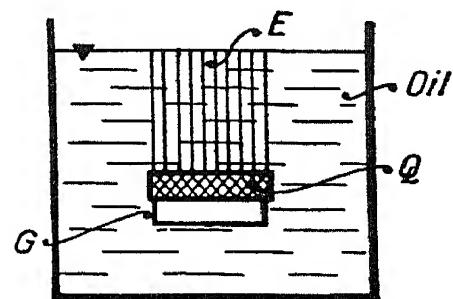


FIG. 40. Gruetzmacher's fixing for quartz.

ways: either a sensitive electrometer is put parallel to the vibrating quartz, measuring the alternating voltage applied to it, or an indicator circuit is coupled inductively with the quartz, the current induced in it being measured by a thermocouple connected to a direct-current galvanometer. This induced current is proportional to  $M\omega i$ , where  $M$  is the coefficient of mutual induction,  $i$  the effective current flowing to the quartz, and  $\omega$  the frequency in circular measure. The E.M.F. given by the thermocouple is then proportional to  $M^2 i^2 \omega^2$ , and the deflection of the galvanometer is a direct measure of the electric energy supplied to the quartz, and hence a measure of the ultrasonic energy  $J$  radiated. As we shall see on p. 43,  $J \sim A^2$ , where  $A$  is the maximum amplitude of the quartz vibration, which, as we saw on p. 14, is directly proportional to the applied alternating voltage, and so to the current  $i$  flowing to the quartz. If the energy supplied to the quartz is not merely to be controlled for constancy, but to be measured absolutely, we may use the following method of comparison given by Becker (36). The quartz is put parallel to a variable condenser of an oscillating circuit, which is loosely coupled inductively to the main oscillator. The effective alternating voltage on the quartz is measured by an electrometer calibrated by direct voltage. In a condition of resonance, the vibrating quartz acts like a capacity having loss. A change-over switch allows the vibrating quartz to be replaced by a small variable capacity with a non-inductive, capacity-free resistance in parallel with it. When resonance, that is maximum electrometer deflection, has been restored by means of the variable comparison condenser, the resistance  $W$  is increased until the voltage  $U_{\text{eff}}$  shown by the electrometer has the same value as when the quartz was inserted. The electric energy supplied to the quartz is then  $N = \frac{U_{\text{eff}}^2}{W}$ .

## CHAPTER II

### THE DETECTION AND MEASUREMENT OF ULTRASONIC WAVES

Very few of the methods used in acoustics over the audible range of detecting and measuring wave-length, intensity, and absorption of sound waves can be used in the ultrasonic region, and then only over the range of lower ultrasonics where the wave-length is of the order of centimetres; these methods fail at higher ultrasonic frequencies because the indicators are in general too large compared with the ultrasonic wave-lengths and give rise to disturbance in propagation. On the other hand, we have in the ultrasonic region, especially for the higher frequencies, a number of special methods both of making the waves visible and of measuring their length and intensity with great accuracy. These are chiefly optical methods which have of late been put forward from various sides, and have led to a whole series of new applications of ultrasonics. In this chapter we will describe the various methods for detecting and rendering visible ultrasonic waves, and give in the case of each method the manner in which it may be used for measuring wave-length, intensity, and so also absorption of the waves.

(a) **Mechanical Method.** The method first described by

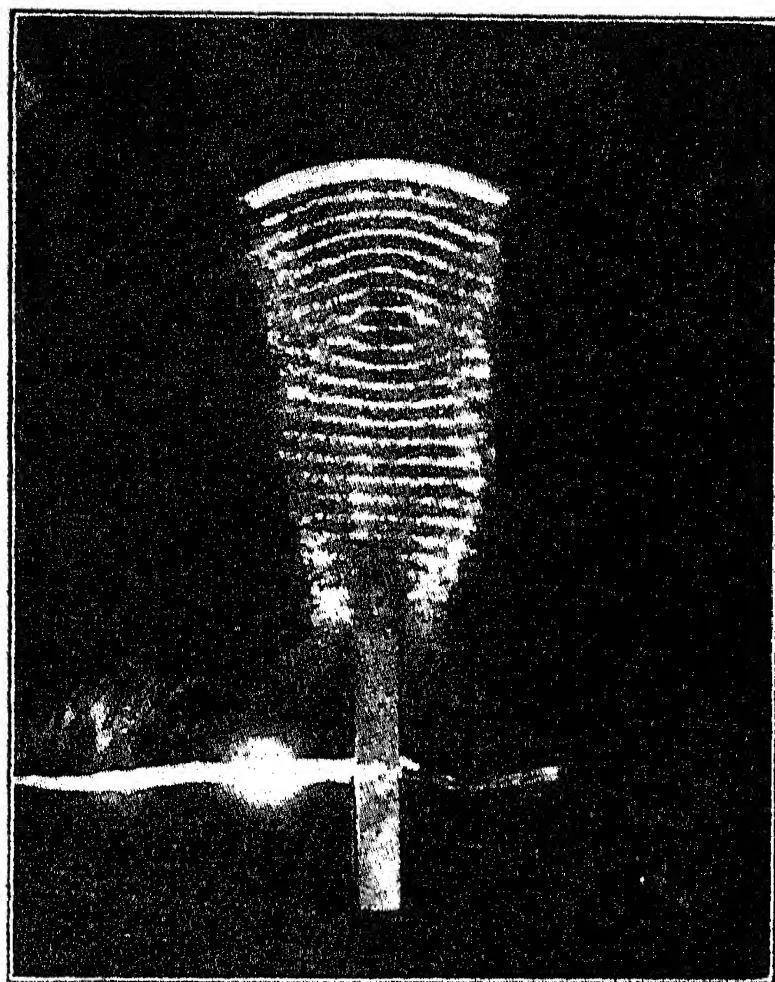


FIG. 41. Stationary ultrasonic wave made visible by lycopodium (Straubel).

Kundt (275, 276) in the year 1866, of making sound waves visible by means of fine dust, may also be used in the case of ultrasonics, as long as the waves are not shorter than a few millimetres. The best fine powder for the purpose is lycopodium ; this arranges itself in the nodes of the sound vibration in the form of narrow ridges, which appear at distances of half a wave-length, and so allow the wave-length to be measured at least roughly. For example, fig. 41 gives a photograph by Straubel (446) in which

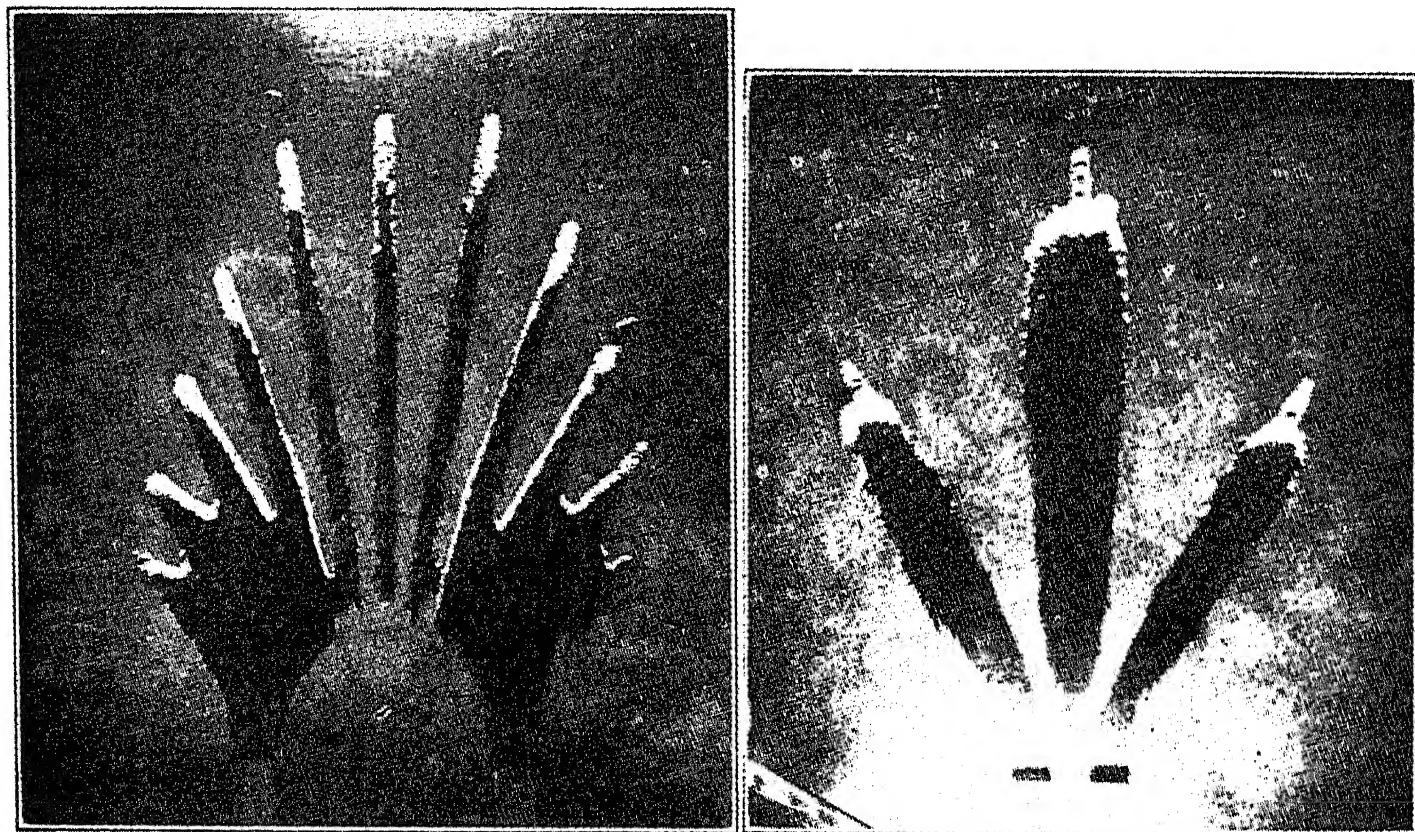


FIG. 42. Radiation characteristic of two ultrasonic quartzes, (a) long, (b) short distance between quartzes (Straubel).

the sound wave emitted from the end of a vibrating quartz rod is made visible. A metal strip bent in a concave form is used as a reflector ; we are able to see plainly the way in which this reflector acts like a concave mirror by the nodal lines rendered visible by the lycopodium. Stationary sound waves may also be made visible in liquids, if, as by Boyle and Lehmann (79, 83, 88), powdered coke is used, which sinks slowly to the bottom of the liquid, and is driven by the sound waves to their nodes. We then get a picture of the stationary waves on the bottom of the vessel. Sound waves travelling through air may also be made visible by

luster figures. The pressure of the sound radiation, and a current of air formed in the direction of its propagation, blow away the luster from a surface at points where the sound waves are travelling. Fig. 42 (a) and (b) give two characteristic examples of this. The sound waves are proceeding from the faces of two similar quartz rods, which are placed at different distances from one another and parallel. As in the case of light coming from a pair of slits, we get interference effects resulting in the formation of a radiation pattern, the directional character of which is the more marked,

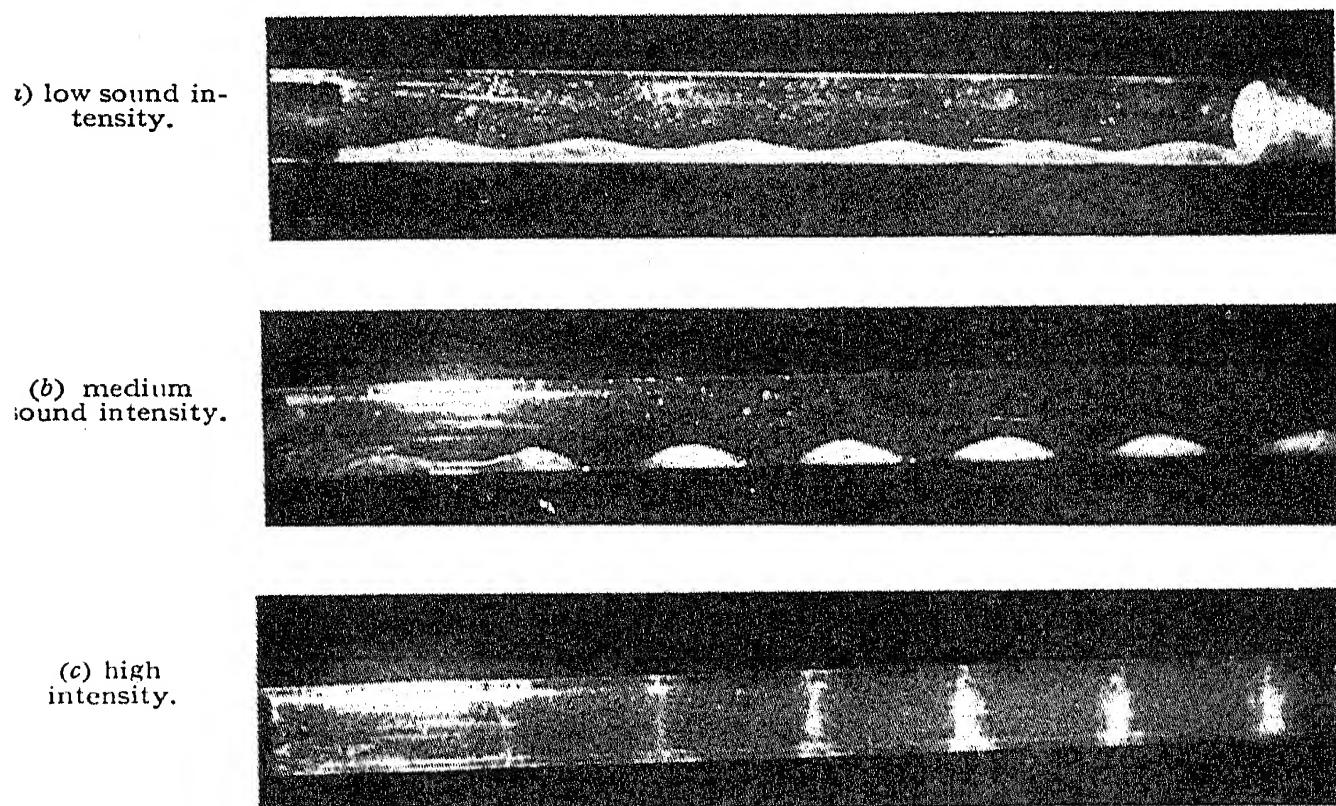


FIG. 43. Rendering stationary sound waves visible in liquids in tubes (Brandt and Freund).

the nearer the two radiating quartzes are to one another. This simple method is naturally not suited to an exact investigation of sound propagation, but simply for giving a rough idea by way of demonstration.

More powerful stationary waves in a liquid result, according to Boyle and his co-workers (76, 80, 91), in the formation of bubbles, which collect in the nodes of motion and so give us a picture of the stationary wave. The actual cause of this formation of bubbles will be discussed later (p. 216). Strong stationary waves in air may be made visible in horizontal tubes by a method given by Dvorak (133), by putting some liquid in the tube, forming a

layer in its lower part. On account of the excess pressure existing in the nodes, the liquid exhibits a periodic rise in level in the loops, which may be rendered visible by casting a shadow of the tube on a screen. Fig. 43 (a) to (c) gives this phenomenon for different sound intensities according to recent experiments by Brandt and Freund (94). When a certain amplitude is exceeded the layer of liquid is completely broken up into sections (fig. 43 (a)), and finally (43 (c)) is sprayed in a thin layer across the tube in the loops of vibration. Brandt and Freund have made use of this method with some improvement for rendering ultrasonics visible. They used the layer of liquid, bent like a cylindrical lens at the loops of vibration, as a lens for forming an optical image, using a straight

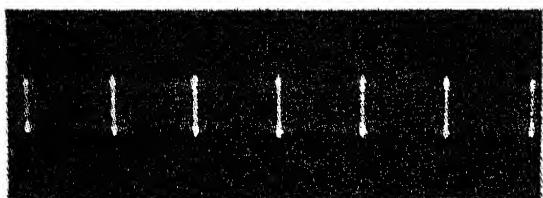


FIG. 44. Bands given by a stationary sound wave in air (Brandt and Freund).

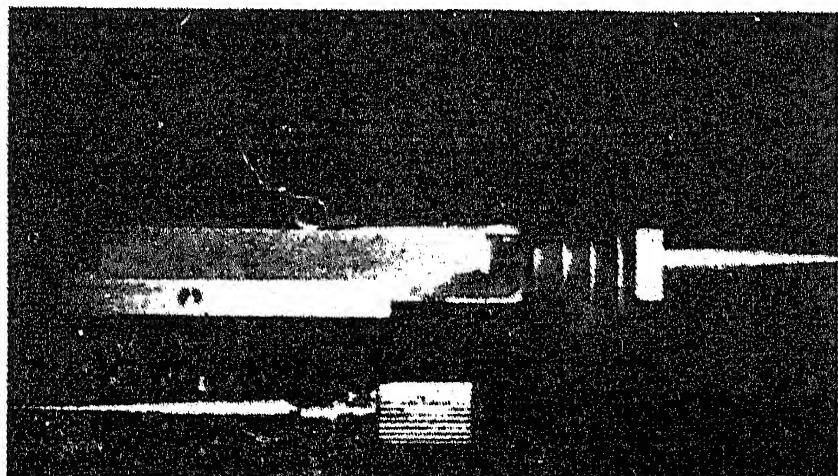
filament glow-lamp placed one or two metres over the tube as object, images of it being formed on a screen lying under the tube. The result is a system of bright lines (fig. 44) enabling a highly accurate measurement of the wave-length of the sound in the gas. A liquid with negligible

vapour pressure may be used in order to avoid disturbances from that cause.

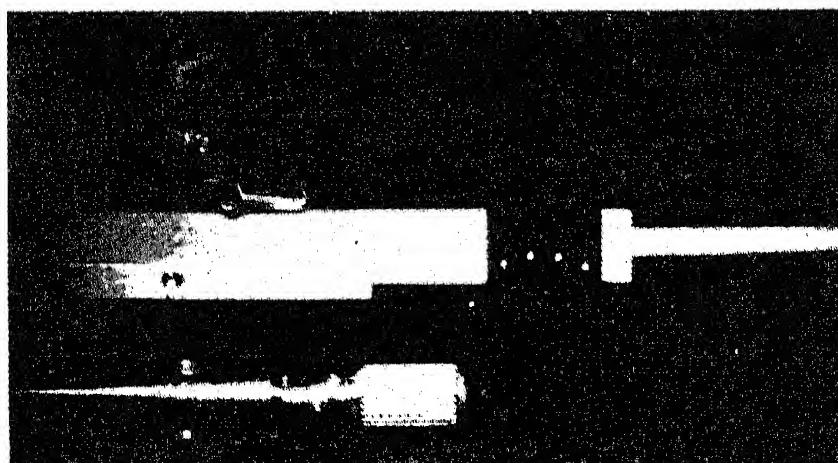
Bücks and Müller (105) have described a very interesting method of observation of stationary ultrasonic waves of great intensity, consisting in the condensation of alcohol mist. If an oscillating quartz rod is placed at a distance of a few half wavelengths from the reflector, and a drop of alcohol is put on its vibrating face, this evaporates and condenses again in the loops of the stationary sound waves, forming strips of mist, out of which small drops of alcohol continually fall. Finally, only single drops of one millimetre diameter are formed, which remain floating in the loops until they finally evaporate. The phenomenon is shown in fig. 45 (a) and (b).

Tobacco smoke, mists produced by salammoniac, hydrochloric acid, and similar substances, may also be used in tubes according to Brandt and Freund (94) and Pearson (354), make the waves visible. The vibrations cause coagulation of the particles of smoke or mist, which then are thrown down very quickly in the nodes. When hydrochloric acid mist is used, we get etched figures on a polished plate of zinc, very like those produced by dust.

The mechanical methods hitherto described are useful simply for exhibiting ultrasonic waves and measuring their length. But another matter of interest in these investigations is the intensity of the waves of the sound radiation. Before describing some



(a)



(b)

FIG. 45. Rendering stationary ultrasonics visible in air by drops of liquid (Bucks and Müller). The upper illustration shows clearly the bands of alcohol mist formed in the loops of the stationary sound wave. In the lower picture the bands of mist have condensed to single drops.

Methods of measuring this, let us define some of the most important acoustical magnitudes. The sound intensity  $J$ , meaning the amount of sound energy passing through a square centimetre in unit time, is given either in  $\text{erg}/\text{cm}^2$ , or in  $\text{mW}/\text{cm}^2$ , and may be represented for plane sound waves by the following relations:

$$J = \frac{\rho v}{2} (\omega A)^2 = \frac{\rho v}{2} u^2 = \frac{P^2}{2\rho v} = \frac{Pu}{2}.$$

Here  $A$  stands for the maximum amplitude of the vibrating

particles of a medium of density  $\rho$ , in which the sound waves of frequency  $\frac{\omega}{2\pi}$  travel at the velocity  $v$ .  $P$  is the amplitude of the oscillating sound pressure and  $u$  is the acoustic quickness (*Schallschnelle*), that is to say the velocity amplitude of the particles of the medium. Further,  $P/A = \rho v \omega$ , the acoustic hardness (*Schallhärte*), and  $P/u = \rho v$ , the acoustic reactance. We see at once that the measurement of the sound intensity is only possible by measurement of one of the magnitudes  $A$ ,  $u$  or  $P$ , or alternatively, the two magnitudes  $u$  and  $P$ . But these methods fail with mechanical receivers in the ultrasonic range, since Rayleigh discs, pressure membranes, and so on, have dimensions too great compared with the sound waves. On the other hand, we are dealing in ultrasonics for the most part with comparatively great intensities on account of the high frequencies, and are enabled therefore to make use for measurement of another magnitude—the sound radiation pressure—often referred to in older literature as the sound pressure. When sound waves meet with an obstacle, they exercise on it, in addition to the alternating pressure already mentioned, a unidirectional pressure, which finds its theoretical explanation in the want of linearity in the wave equation when account is taken of the quadratic terms. According to Rayleigh (376), the sound radiation pressure  $S$  is given by the relation

$$S = \frac{1}{2}(\kappa + 1) \frac{J}{v}, \text{ where } \kappa \text{ is the ratio of the specific heats and } v \text{ the}$$

velocity of sound. Since  $J$  is proportional to  $P^2$  and also to  $A^2$ , according to the last equation but one,  $S$  must also be proportional to the square of the alternating sound pressure, or the square of the amplitude of motion of the vibrating particles. In the case of a piezoquartz used as source, the amplitude of vibration, as shown on p. 14, is proportional to the applied alternating voltage, so that the sound radiation pressure also increases as the square of this voltage, a fact confirmed by measurements.

Before we come to the methods of measuring sound radiation pressure, we will give a few figures concerning the alternating sound pressure produced by a vibrating quartz in liquids, as well as the sound radiation pressure and the accompanying velocity and acceleration of the vibrating particles of liquid. We assume a quartz which at a frequency of  $N = 300$  kHz gives a sound intensity  $J$  of about  $10 \text{ W/cm}^2$ , and we take water as the liquid

om which the sound waves are propagated. From the relation  $=P^2/2\rho v$ , we get the alternating sound pressure amplitude  $=\sqrt{2J\rho v}$ ; for  $J = 10 \text{ W/cm}^2 = 10^8 \text{ erg/cm}^2$ ,  $v = 1484 \text{ m/s}$ , and  $=1$ , we get  $P = \sqrt{2 \times 10^8 \times 1.484 \times 10^5} = 5.4 \times 10^6 \text{ dyn/cm}^2 = 5.4$  atm, that is to say, the pressure oscillates in the liquid periodically between 5 atm overpressure and 5 atm tension or suction. The sound radiation pressure is given by  $S = \frac{1}{2}(1 + \kappa) \frac{J}{v}$ ; putting in

numerical values we get  $S = \frac{1}{2} \cdot 2 \frac{10^8}{1.484 \times 10^5} = 674 \text{ dyn/cm}^2 = 0.655 \times 10^{-3} \text{ atm} = 0.687 \text{ gr/cm}^2$  (gr = gram weight).

The velocity amplitude of the water particles is got from the equation  $J = \frac{\rho v}{2} u^2$ ; it is  $u = \sqrt{\frac{2J}{\rho v}}$ . In our case this gives us  $= \sqrt{\frac{2 \times 10^8}{1.484 \times 10^4}} = 36.7 \text{ cm/s}$ . This velocity amplitude corresponds to an amplitude of vibration of the particles of  $A = u/2\pi N$ . This for a frequency of 300 kHz, given by a quartz 1 cm thick vibrating in its thickness, has the value  $1.99 \times 10^{-5} \text{ cm} = 0.199\mu$ , that is to say the water particles are only vibrating with amplitudes of the order of colloidal dimensions. On the other hand, we get for the acceleration  $b$  of the water particles the value  $b = 2\pi N u$ ; this gives us an acceleration of roughly  $7 \times 10^7 \text{ cm/s}^2$ , that is to say an acceleration about  $10^5$  times greater than gravity, and one otherwise only attainable by the ultracentrifuge, it is further to be noted that in the sound waves the acceleration changes in reaction  $N$  times in a second.

The measurement of sound radiation pressure is made by diometers. An apparatus of this sort is formed in principle by a sort of torsion balance which carries on one side a mica plate, which is struck by the sound, while on the other side there is a small balancing weight. A construction of this description is shown in fig. 46 (a). No radiation reaches the back side of the plate on account of the shortness of the ultrasonic waves. The radiation pressure exerted on the front of the plate is greater the more complete the reflection of sound from it. Now if a sound wave travelling in a medium of density  $\rho$  at a velocity of  $v_1$  meets at right angles a plate of thickness  $d$ ,

density  $\rho_2$ , and made of material carrying sound at a velocity  $v_2$ , we have a reflection of the wave, given by

$$R = \left( \frac{\rho_1 v_1 - \rho_2 v_2}{\rho_2 v_2 + \rho_1 v_1} \right)^2 / \left[ 4 \cot^2 \frac{2\pi d}{\Lambda_2} + \left( \frac{\rho_1 v_1 + \rho_2 v_2}{\rho_2 v_2 - \rho_1 v_1} \right)^2 \right],$$

where  $\Lambda_2$  stands for the wave-length of the sound in the plate. This relation, given by Boyle and Rawlinson (84; see also 78, 81), leads to a maximum of reflection for  $d = \frac{(2n-1)\Lambda_2}{4}$ , which is the better, the greater the value of the quotient of the sound resistances of the liquid ( $\rho_1 v_1$ ) and the plate ( $\rho_2 v_2$ ). With very

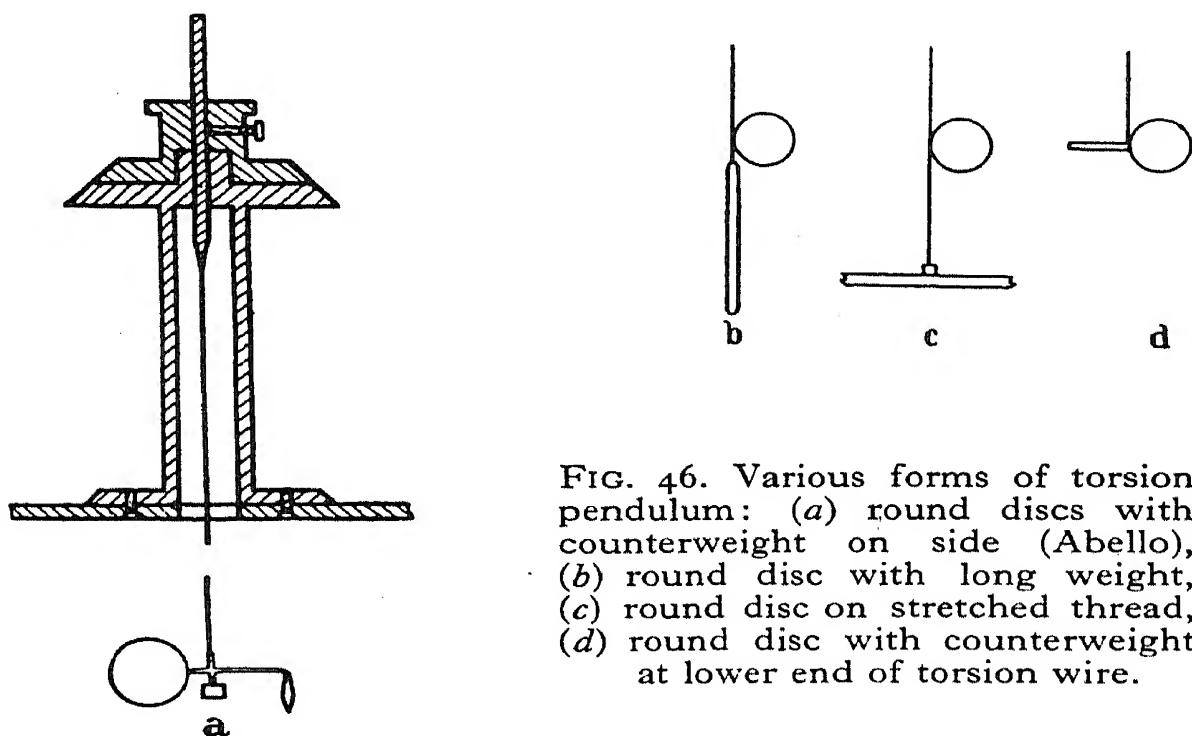


FIG. 46. Various forms of torsion pendulum: (a) round discs with counterweight on side (Abello), (b) round disc with long weight, (c) round disc on stretched thread, (d) round disc with counterweight at lower end of torsion wire.

thick plates—that is to say, when the sound passes from one medium ( $\rho_1 v_1$ ) to a second ( $\rho_2 v_2$ )—the above formula may be simplified into

$$R = \left( \frac{\rho_1 v_1 - \rho_2 v_2}{\rho_1 v_1 + \rho_2 v_2} \right)^2.$$

This gives us for the percentage of sound which is reflected from the boundary, water-steel 86 per cent., for water-glass 66 per cent., for oil-steel 88 per cent., for oil-glass 70 per cent., and for mercury-steel 11.5 per cent. On the other hand, for the passage from liquid to air or *vice versa*, we get a value of 100 per cent. Hence Boyle and his co-workers used as torsion plates for sound measurements in liquids two parallel thin mica-

ates with a small air space between them. Fig. 46 (b), (c), and (d) give a number of other forms of torsion balance, likewise described and investigated by Boyle (89). King (247) has recently given exact formulæ for the radiation pressure on rigid very thin diometer discs, taking into account diffraction and inertia. These measurements with torsion are disturbed by a current of liquid sent out by the source, which is always observed with high-frequency vibrating piezoquartzes both in air and in liquids, and has been called the 'quartz wind.' These currents of air—the same phenomenon appears with quartz vibrating in liquids—are formed by the vibrating quartz surface first pushing away the air in contact with it, but not completely pulling back the air which has been pushed forward; hence new air streams from the sides into the partial vacuum produced. This new air is then likewise set in motion at the next forward vibration of the quartz. The phases of compression and expansion in the case of the high-frequency vibrations are not longer to be regarded as equal and opposite close to the vibrating surface (324, 468, 467, 105). These air currents may be avoided in ultrasonic vibration, either by working at greater distances from the source of sound, at a point where the air currents are already much weaker, or by producing the sound waves in a separate place from the vessel in which they are investigated. In this case it is necessary to choose such a thickness for the separating wall, that as large a part as possible of the sound energy is let through. This thickness, as we see from the equation given above, is given by  $d = n\Lambda_2$ . Investigations on the transparency or sound of walls of different thickness, as dependent on the ratio of thickness to wave-length, have been made by Boyle and D. O. Sproule (85) and Biquard (61). An optical experiment on demonstrating the wall thicknesses having maximum transmission for ultrasonics has been given by Hiedemann and Asbach (204; see also p. 89).

Sörensen (437) has described a balance for measuring the radiation pressure of very intense ultrasonics travelling in a vertical direction in oil. It has the advantage that the radiation pressure is measured directly in  $\text{gr}/\text{cm}^2$  by adjustment of a weight, and that the reflecting plate, after adjustment of the balance, is always at the same point in the sound field, so that the beam of sound is not disturbed, but, meeting the plate at right angles,

is only reflected or in part absorbed. A radiation pressure balance for sound waves travelling horizontally in a liquid is given by Oyama (341). A simple sound-pressure meter suitable only for relative measurements is described by Malov and Rschevkin (312). It consists of a thin aluminium lever, pivoted so as to turn about a horizontal axis, and carrying at its lower end a small disc, which is acted on by the sound waves. The deflection of the lever, which dips down from above into the field of sound to be investigated, may be read off on a scale.

Finally, we must mention two very simple methods which may be used for relative intensity measurements of ultrasonics. Richards (379, 380) uses for this purpose a thick-walled glass

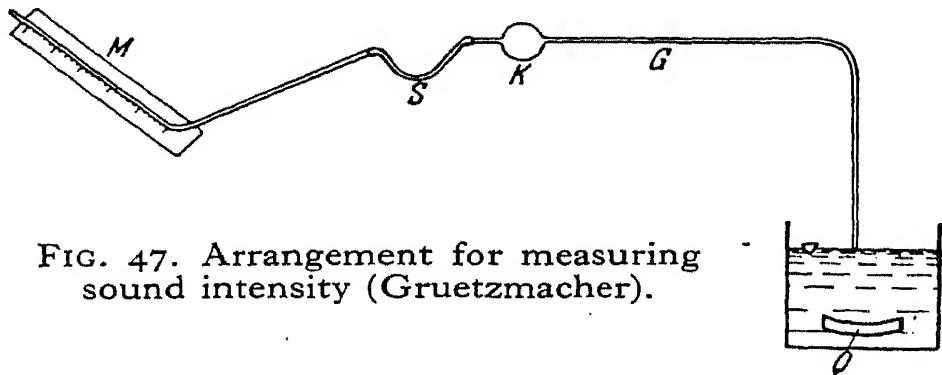


FIG. 47. Arrangement for measuring sound intensity (Gruetzmacher).

funnel with an approximately exponential opening, and joined to a capillary of about 1 to 2 mm diameter. The funnel is dipped in the liquid in which the field of sound to be investigated is present, the liquid then runs up the capillary. If the sound waves meet the opening of the funnel at right angles, the sound radiation pressure causes the surface of the liquid in the capillary to rise, and this rise is the measure of the sound intensity.

A similar method for comparing ultrasonic intensities has recently been given by Gruetzmacher (176). The experimental arrangement is given diagrammatically in fig. 47. A glass rod *G* dips at one end into the ultrasonic field, which in this case consists of sound waves travelling vertically in a vessel full of oil. At the other end of the glass rod there is a glass bulb *K*, the interior of which is in connection with the manometer *M* through a rubber tube *S*. The glass rod is held by a rubber thread. The ultrasonics are lead to the bulb by the glass rod even round the bend, its radius being large compared with the wave-length, and give rise to an increase of temperature of the air in the bulb ; this being shown by the manometer and

forming a measure of the sound intensity. A characteristic of this arrangement is that the rise of pressure takes place almost instantaneously on account of the low thermal capacity.

A somewhat simpler form of the same method is used by Pagnon and Biancani (129) for an exploratory measurement of intensive ultrasonic fields such as are used for chemical and biological purposes. A glass rod about 5 cm and 5 mm thick, broad out at its lower end to a disc, is fused at its upper end to the bottom of a test-tube filled with oil and containing a thermometer. The lower end of the glass rod dips into the field under investigation, the waves then running through the rod into the oil, where they are absorbed. The heat developed in a certain time, as measured by the thermometer, is a measure of the intensity of the ultrasonics.

(b) Thermal Ultrasonic Receivers. A transformation of sound energy into electrical energy may be accomplished, for example, by way of the heat developed, so that apparatus for the investigation of ultrasonic fields may be based on it; these are referred to as thermal receivers or 'thermo-microphones.' The commonest types of these depend upon the change in resistance of thin wires, gently heated by a current, when acted upon by the ultrasonic field. The phenomena produced, in some ways very complex, have been investigated both theoretically and experimentally simultaneously by von Hippel (217, 218), and in several publications by Waetzmann and co-workers (57, 158, 167, 327). There are three chief effects. At the nodes of a stationary sound wave we have the particles of the medium at rest, but on account of the adiabatic changes of pressure they are subject to changes of temperature, so that a metal wire placed in the node is cooled and heated relatively to a fixed temperature and suffers a periodical change in its electric resistance. This case is described as the 'node effect.' The conditions are different in the loops of a sound wave. Here the particles of the medium have the temperature of their surroundings, but a directed velocity. They therefore exert a cooling effect on a heated wire, causing periodical reduction in its resistance of double the frequency of the sound, this being named the 'vibration effect.' Finally, we may have the case that the alternating current of air is combined with a unidirectional current, which may be formed, for example, by a component of

the convection current formed by the heated wire, and having the direction of the sound vibrations. In this case, where the cooling effect of the convection current is alternately increased and decreased by the vibration of the air, we speak of a 'convection current effect.' The high frequencies in ultrasonics prevent in general the periodic temperature changes from being directly observed, on account of the thermal capacity of the wires, though such observation is possible in the audible range ; we have therefore to determine the steady difference between the mean temperatures of the wire with and without sound. This we shall call the 'steady cooling effect.' For this purpose the wire forms one arm of a highly sensitive Wheatstone bridge.

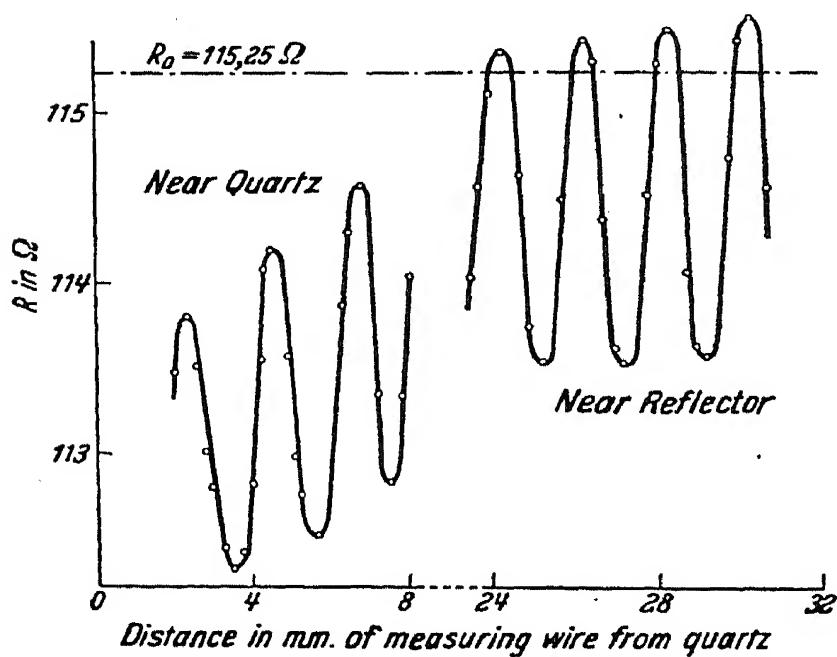


FIG. 48. Stationary sound wave in air measured by hot wire.

waves. Measurements of this sort were first carried out for ultrasonics by Müller and Kraefft (328) and also Bücks and Müller (105). Fig. 48 shows a stationary wave of frequency 81.7 kHz measured by a hot wire. The abscissæ give the distance of the wire from the vibrating quartz surface, and the ordinates its resistance. It is noticeable that on the one hand the resistance of the wire does not attain its stationary value  $R$  in those nodes near to the quartz, and that on the other hand this stationary value is actually exceeded in the nodes close to the reflecting plates, so that the wire is somewhat overheated there. The reason for this fact is given by the air currents proceeding from the quartz, already mentioned on p. 47. Near to the quartz

The platinum wires used must not be greater in diameter than a few  $\mu$  (what is called 'Woollaston' wire) ; their length is about 15 to 20 mm. Since they are so small they cause hardly any disturbance of the sound field, this being a great advantage of these thermal receivers, which are suitable both for mapping stationary waves and for measuring the intensity of travelling

These air currents strongly cool the heated wire, but this effect becomes smaller with increase of distance; when the air currents meet the reflecting plates eddies are formed which disturb the convection current from the heated wire, resulting in its being more strongly heated. Apart from these disturbances this method gives the wave-length with an accuracy of about  $1\%$ .

Richardson (389, 390) also made ultrasonic measurements with these hot-wire instruments, and found an almost linear relation between the reduction in resistance of the heated wire and the amplitude of the sound, showing that these hot wires are suitable for quantitative measurements of the intensity and absorption of ultrasonics in gases. Richardson also gives another experimental arrangement, which makes use of the periodic cooling effect. He connects two wires heated almost to redness with two primary windings of a transformer, the secondary being either connected to a thermo-galvanometer, or through an amplifier to a heterodyne receiver. In the latter case we get a beat note. The deflection of the galvanometer, or the loudness of the beat note, is dependent on the difference of phase between the two primary currents. It is therefore possible to measure the phases in the ultrasonic field, that is to say the wave-length, by moving the wires relatively to one another. According to this author the method is still of use up to 200 kHz. But its construction calls for great care, since the periodic changes of resistance are very weak, and the wires have to be carefully shielded from the direct action of the high-frequency field with which the quartz crystal used as source is being driven.

Investigations of the energy distribution of ultrasonics in different liquids with a resistance thermometer made of iron wire about 1.5 cm long and  $15\mu$  thick, and not preheated, were made by Malov (311).

The use of thermocouples enclosed in an envelope absorbing sound has occasionally been proposed for ultrasonic measurements. Apart from Malov, Richards (381), investigating the passage of ultrasonics through plates of different material and thickness, made use of a thermopile surrounded by a sound-absorbing material such as ebonite, fibre, bakelite, or pitch, and responding to ultrasonic energies as low as  $0.01 \text{ W/cm}^2$ . Johnson

(239) gives some data concerning the most suitable dimensions of thermocouples for measurements in sound fields.

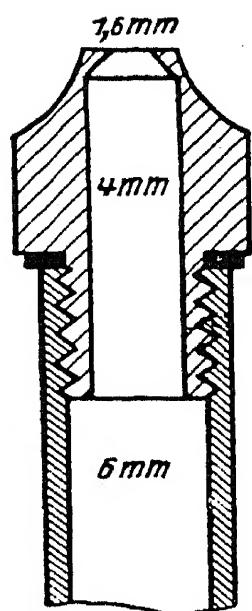


FIG. 49. Jet for sound-sensitive flame.

This section may be closed by a short reference to the sound-sensitive flame discovered by Leconte, and introduced into acoustics by Tymball; this forms a highly sensitive indicator in ultrasonic work as well. A town gas flame, burning at a circular jet about 1.5 mm diameter, may be sensitized, as Zickendraht (482) has recently shown, by disturbing the current of gas by means of a platinum wire, pushed from the side into the opening of the jet. This sensitivity to sound may be more conveniently produced by a conical constriction of the jet, as shown in section in fig. 49. When sound waves strike the flame, it is deformed

by them, as shown in fig. 50 (b) for the direction of the sound, and 50 (c) for a direction at right angles; 50 (a) shows the appearance of an undisturbed flame.

angles; 50 (a) shows the appearance of an undisturbed flame.

The sensitivity of the flame is greatest when the gas pressure is about 8 cm of water, and when the sound meets the flame close to the jet. Since the flame responds to the velocity amplitude of the sound waves, its sensitivity increases with increasing frequency. Brown (104) recently investigated the mechanism of sensitive flames more closely, and showed that their sensitivity was caused by the formation of eddies over the end of the jet; these were made visible in very beautiful photographs. The close connection between this eddy formation and the production of eddies when sound is produced at sharp edges has recently been pointed out by Krüger and Casper (273).

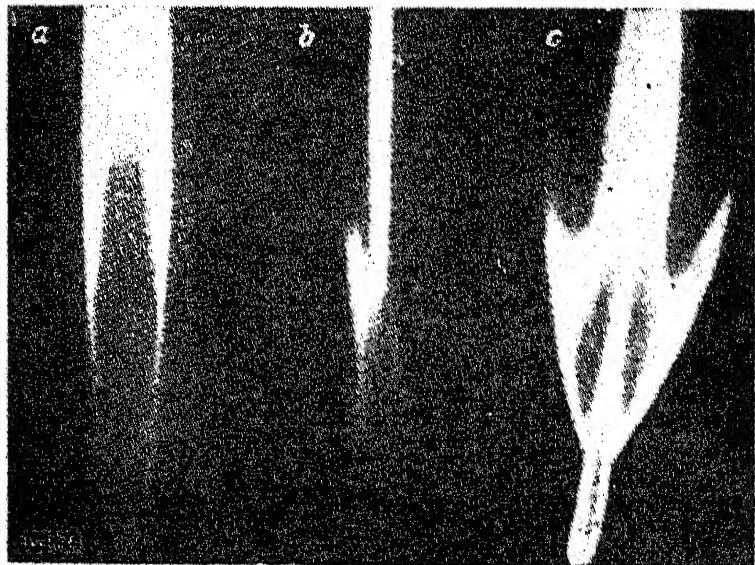


FIG. 50. Sound-sensitive flame (a) without, (b) and (c) with, sound acting in two directions at right angles to one another (Zickendraht).

been pointed out by Krüger and Casper (273).

(c) Electrical Sound Receivers. The only electrical receivers

itable for use in ultrasonic work are the piezoelectric crystals, since all other forms of microphone are too insensitive, at least for high ultrasonic frequencies, on account of their great mass. Cerdote (403) has described the construction of a very small condenser microphone, having an aluminium diaphragm 0.8 cm diameter and a few  $\mu$  thick, and sensitive up to frequencies of 100 kHz.

Piezoelectric receivers act in the following way. If a wave meets the piezoelectric plate in one of its vibration directions, and has the same frequency, the plate is set in mechanical vibration, and the resulting mechanical deformation causes electric charges to be liberated on the surfaces at right angles to the  $X$  axis by the direct piezoelectric effect. The sign of these charges, and hence the differences of potential produced with a given electrode capacity changes periodically with the frequency. Langevin (35) was the first to suggest the use of such piezoelectric receivers, and proposed to amplify the resulting alternating EMF and detect it by a beat method.

W. H. Glans (195) carried out the first quantitative ultrasonic measurements with piezocrystal receivers. The quartzes used by him were in the form of rods, oriented as in fig. 16. The sound waves travelling in the direction of the  $Y$  axis meet the end face of the quartz. The quartz electrodes were connected, as shown in fig. 51, with a crystal detector  $D$ , which is put in parallel with a highly sensitive galvanometer  $G_1$ .

This receiving circuit could be calibrated by replacing the quartz  $Q$  by a resistance  $R$ , by means of the change-over switch  $U$ ; this resistance is then traversed by an alternating current having the natural frequency of the quartz, and measurable by a thermocouple  $T$  and galvanometer  $G_2$ . This current was produced by an oscillator in the coil  $L$ . We then have a deflection of the galvanometer  $G_1$  proportional to the mean square of the current delivered by the quartz receiver, and since this again is proportional to the pressure amplitude of the sound waves received, the deflection is proportional also to the mean square of the

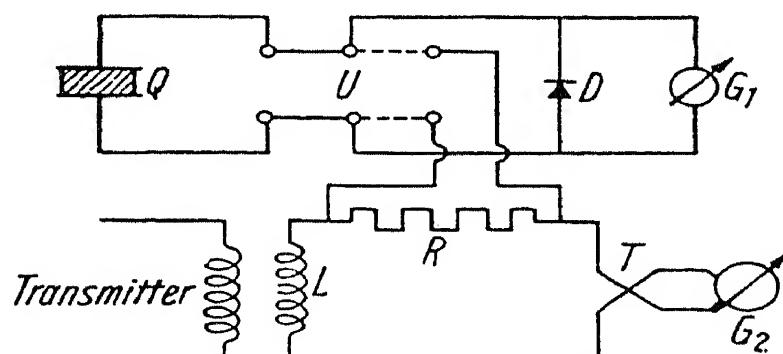


FIG. 51. Arrangement for calibrating quartz used as sound receiver.

pressure amplitude, that is to say the intensity of the wave received. On account of the very small damping of the vibrating quartz, and its resulting high selectivity, a quartz used as receiver is sensitive only to waves of its own natural elastic frequency, but insensitive to all other motions, and also not disturbed by the air currents to which we have frequently referred.

Since it is in general very difficult to get two quartzes, one to be a source and the other a receiver, adjusted within one part in 1000 of one another as regards their natural frequencies by grinding, it is necessary to make use of the method of electrically tuning the receiving quartz to the frequency of the oncoming wave.

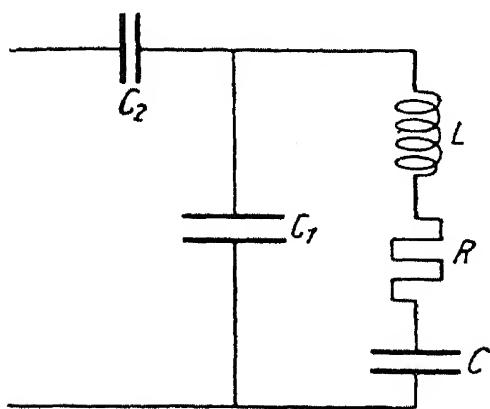
This tuning (see p. 32, vario-holder) was first experimentally observed by Cady (106), and is effected by changing the distance of one electrode from the quartz surface. According to Dye (135) (see also the later papers of Watanabe (470)

FIG. 52. Electric circuit substituted for vibrating quartz.

and van Dyke (136)) the vibrating quartz may be replaced as regards its electrical effect by an electric circuit, fig. 52.  $C_1$  is formed by the static capacity of the quartz, parallel to it being an inductance  $L$  in series with a resistance  $R$  and a capacity  $C$ .  $L$  corresponds to the mass,  $R$  the mechanical resistance, and  $C$  the rigidity of the crystals. If we now have a space between the quartz surface and the metal electrode near it, this acts like a capacity  $C_2$  put in front of the whole arrangement (see fig. 49). If the electrode distance is changed, this has the same effect as putting  $C_2$  out of tune, and so changing the natural frequency of the whole substitutional circuit—that is to say, the natural frequency of the quartz. The relative frequency change  $\Delta N/N$ , resulting from a change of  $\Delta a$  in the distance  $a$  of the electrodes from the quartz surface, is given, according to Dye, by

$$\frac{\Delta N}{N} = \frac{d}{300} \cdot \frac{\Delta a}{[(a + d/\epsilon)^2 + \Delta a(a + d/\epsilon)]},$$

where  $d$  is the thickness of the quartz in the  $X$  axis, and  $\epsilon = 4.3$  the dielectric constant of the quartz. In the case of a quartz with metallized surfaces, that is to say with electrodes in



## ELECTRICAL RECEIVERS

fixed contact, a frequency change may be brought about by inserting a small variable condenser in the lead to one of the electrodes.

Instead of the crystal detector used for rectifying the high frequency alternating voltages from the receiving quartz in fig. 5 it is advantageous also to use an electrometer valve or an audio receiver with subsequent low frequency amplification. Fig. 5 shows a circuit given by Abello (1, 2), in which the alternating voltage given by the receiving quartz is first amplified at high

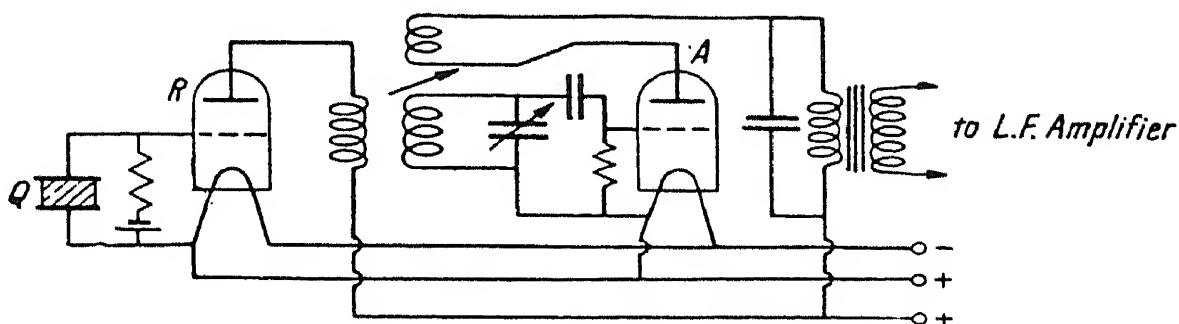


FIG. 53. Quartz sound receiver with high-frequency amplifier and retroactively connected audion (Abello).

frequency by the valve *R*, and then rectified by the retro-coupled valve *A* and made audible as a beat. The low frequency alternations of the beat tone may once more be amplified and measured by a rectifier and milliammeter. A similar circuit has also been described recently by Yeagley (479, 480). These constructions require great care in screening the receiving quartz and its circuit connections, and also the amplifier, from the high frequency electromagnetic field of the quartz source. Otherwise very disturbing interference phenomena, first pointed out by Hehlgas (195), result from the superposition of the currents generated in the receiving circuit by the sound, upon those induced directly by the electromagnetic field. In addition to the authors already mentioned, Grossmann (172, 173) has also worked with quartz as sound receivers, and carried out in this way absorption measurements of ultrasonic in gases. Quartzes have very recently been used as the receivers for low-frequency modulated ultrasonics, and also for sound absorption measurements in air by Kuntze (277). Sokoloff (434 a) describes the construction of an ultrasonic indicator containing a Rochelle salt crystal as piezoelectric receiver; it was used as an indicator for measuring the amplitude of vibration of ultrasonic generators.

It is possible in certain cases to use the transmitting quartz as receiver also. Langevin (285, 286), using ultrasonic waves for echo sounding, already recorded the reflected wave by using as receiver, acting on an oscillograph, the quartz which the moment before had sent out the wave (p. 197). If a sound wave proceeding from a vibrating quartz is allowed to fall on a plane reflector in such a way that a sound wave is formed, between the face of the vibrating quartz and the plate, we get, as the position of the reflecting plate is changed, a periodically varying reaction of the reflected sound waves on the transmitting quartz ; the variations may be detected in a number of ways, and form a very sensitive and much used arrangement for exact measurement of wave-length. The reaction of the reflected sound waves on the transmitter will be a maximum when the motion of the particles at the quartz surface, caused by the primary sound wave sent out by the quartz, is oppositely directed to the motion of the particles caused by the reflected waves. It is at once clear that maximum effects of this description will occur periodically as the reflecting plate is shifted through a distance  $\Lambda/2$ . According to Hubbard (225) the air or liquid column between the quartz surface and reflecting plate may be regarded together with the vibrating crystal as a mechanical system, the apparent resistance of which changes periodically with the change in distance of the reflector. But in accordance with the electrical substitutional circuit of fig. 49, able to take the place of the vibrating crystal, the values of the self-induction and the resistance must also change periodically, a fact which may be observed in various ways in the transmitter used for exciting the quartz. For example, the voltage at the quartz electrodes, as observed with an electrometer valve or a glow-lamp, changes, as also does the high-frequency current passing through the crystal, as measured by a thermocouple, and finally also the direct anode current of the transmitting valve will also change periodically. These electrical changes allow the positions of resonance and so the position of the reflector to be determined very accurately. Pierce (361) already measured in this way wave-lengths of ultrasonics in gases. Fig. 54 shows one of his first series of measurements, the abscissæ being the distance of the reflecting plate from the quartz, and the ordinates the deflections of a milliammeter in the anode circuit of the trans-

itting valve, as in fig. 33 (a). Hundreds of current maxima and hence an equal number of acoustic resonance positions of the reflecting plate may be determined in this way, resulting in great accuracy of measurement of wave-length (see also chapter III (a)). Heegner (193, 194) and Dye (135) investigated more accurately the acoustic influence of the reflected sound waves on the quartz vibrations, and measured quantitatively the increase in damping so caused and the change in frequency of the vibrations. Hubbard and Loomis (227 to 230) have

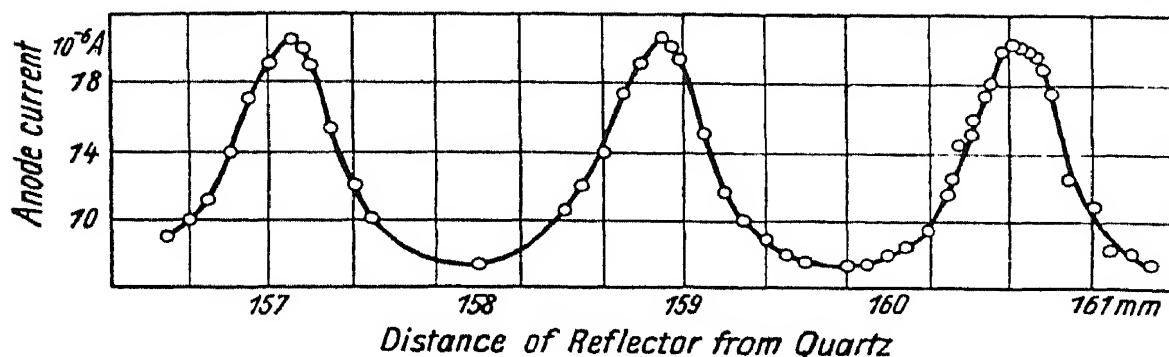


FIG. 54. Stationary sound wave in air measured by the reaction of the wave on the source (Pierce).

shown that this change of frequency may be determined by a beat method, and may likewise be developed into a method of acoustic wave-length measurement. For this purpose, the quartz vibration frequencies are made to beat with a second frequency generated by a quartz-controlled oscillator, producing a beat of about 1 kHz, which is then compared with the standard note of an electrically driven tuning-fork. If a change in the frequency of the quartz is now produced by a shift of the reflecting plate, with the production of the beat note, the change in frequency can be compensated by adjustment of a condenser in the oscillating circuit of the quartz. This allows on the one hand the positions of the reflecting plate to be determined very accurately from the periodic changes in the adjustment of the auxiliary condenser, these positions being  $\Lambda/2$  distant one from the other; and, furthermore, the frequency change, and hence the accompanying change in wave-length, though very small, is put right each time. This method gives us one of the most exact interference methods for the measurement of ultrasonic wave-lengths. This acoustic interferometer allows also of the measurement of absorption. For if we have between transmitter and the reflector a sound-absorbing medium, the intensity of the

reflected waves, and hence their reaction on the transmitting quartz, decreases with increasing distance between the quartz and the reflector, and this decrease allows the absorption coefficient to be calculated (for details see p. 158). The piezoelectric crystals thus used as receivers may theoretically be replaced by a similar use of magnetostriction rods, making use of the reciprocal magnetostriction effect; Pierce (365) has also described the circuits and applications of this method. However, these devices are in general very much less sensitive than the piezoelectrical, and call for more complicated valve circuits, when applied, for example, to the method of reaction of the sound waves. The echo sounding apparatus of the Atlas-Werke A.G. in Bremen, and of the Firma Electroacoustic in Kiel have recently embodied magnetostriction rods as receivers, only, however, for very low ultrasonic frequencies of about 20 to 30 kHz (278).

(d) Optical Methods. Although A. Toepler (461, 462, 463) had already made visible the sound waves produced by a spark, using an optical striation method, more recent optical methods for detecting sound waves have only been described and worked out in the last few years, since the art of producing ultrasonics has been understood. The new optical methods now to be described are all of them only applicable to ultrasonics, where the waves are sufficiently short, as opposed to methods hitherto described, which are equally valuable for audible frequencies.

1. The Striation Method. Toepler's striation method gives a direct picture of the sound waves, since those parts of the

medium whose index of refraction is changed by the sound wave become visible, that is to say in the case of a stationary wave only the pressure nodes remain dark. Fig. 55 shows the

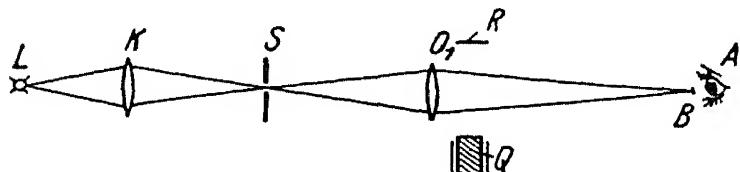


FIG. 55. Optical arrangement for rendering sound waves visible by the striation method.

optical arrangement necessary for this method. A circular diaphragm or slit *S* is strongly illuminated through a condenser *K* by a light source *L*, and a sharp image of it is produced at the point *B* by an objective *O*. The image of the diaphragm or slit is covered with a screen of equal size, so that no direct light finds its way into the eye at *A*. If a stationary sound wave is generated in

nt of the objective  $O$ , for example, by reflecting a wave sent by a quartz  $Q$  at a reflector  $R$ , the points in the sound wave which a change of refraction takes place divert the light, which is past the screen  $B$  into the eye, so that we then see a picture of the stationary wave, in which the pressure nodes remain dark and the loops are bright. This phenomenon may also be photographed, by putting an objective at  $A$  producing an image of the sound wave on a screen or on a photographic plate. The photographs of the overtones of a quartz plate given in figs. 18-20 were made in this way. The arrangement is the more sensitive, the greater the distance between the objective  $O$  and the diaphragm  $B$ , for then very slight changes in refractive index are enough to cause light to get past the screen  $B$ . It is therefore possible to work with a somewhat larger screen, rendering the experiment easier to manage, and yet get a perfectly black field. On the other hand, Bär (22) has shown that the illumination of the arrangement is not increased.

the use of a long focus objective at  $O$ , and that the experiment may be performed successfully also with a short focus objective. But it is important that the objective  $O$  should itself be completely free from striæ, since these also appear in the field, and disturb the picture of the sound waves. This striation method, which may also be described as a dark field method, was first used by Tawil (457) for ultrasonics produced by a piezoquartz.

This striation method for rendering stationary ultrasonic waves in gases visible has recently been improved by Pohlmann (368) as shown in fig. 56. An arc lamp  $B$  throws a beam via a condenser through the small mirror  $S_1$  on to the slit  $Sp$ , a sharp image of which is formed by the long focus objective  $O$  ( $f=2m$ ) in the plane of the slit, via the mirror  $S_2$ . The image of the slit is

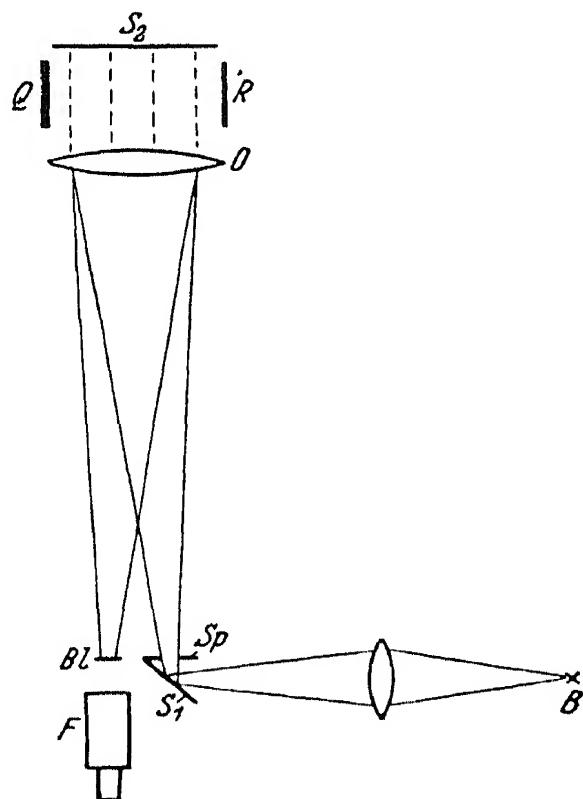


FIG. 56. Pohlmann's arrangement for rendering sound waves visible in air by the striation method.

again covered by a screen *Bl*, so that no light reaches the telescope *F*, which is focussed on the stationary sound wave generated by the quartz *Q* and reflector *R* between the mirror *S<sub>2</sub>* and the objective *O*. The arrangement is similar to an autocollimation method, and the light passes twice through the sound wave, which is equivalent to using a greater depth of wave, and results in a greater reflection of the light in the pressure loops for a given intensity of sound—that is to say, a given change of refractive index. Fig. 57 shows a photograph made by Pohlmann in this

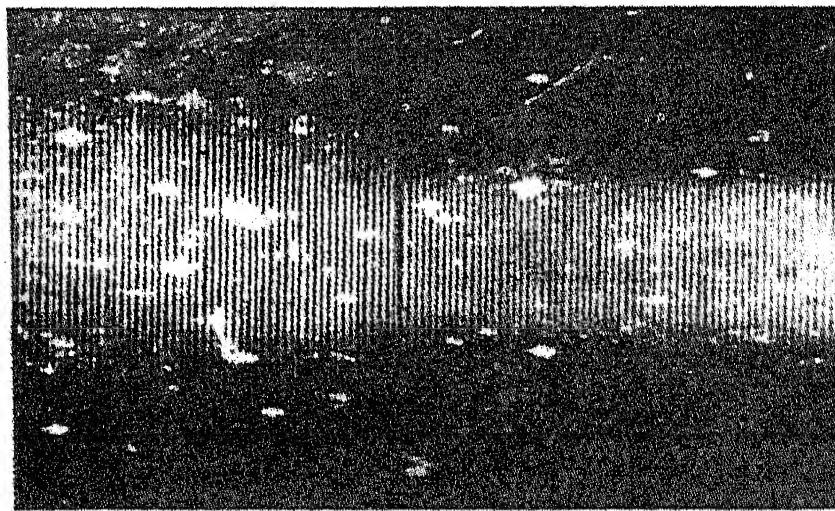


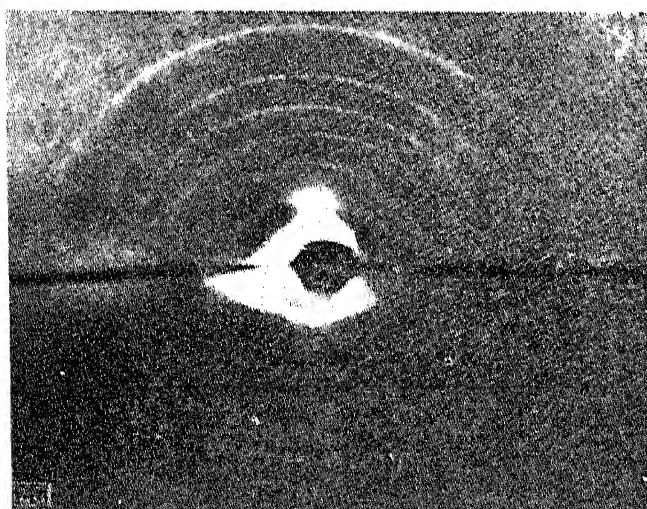
FIG. 57. Photograph of a stationary sound wave rendered visible by striation method (Pohlmann).

way of a stationary sound wave in air, having a wave-length  $\Lambda = 0.4$  mm.

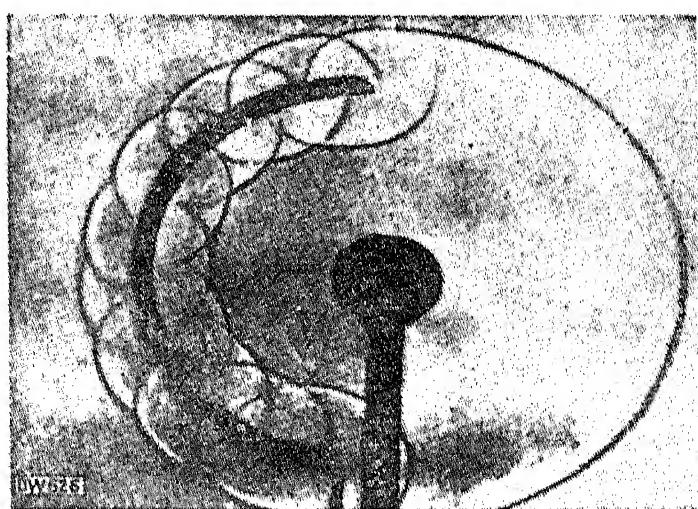
The striation method is naturally applicable in the first place only to stationary waves. Travelling waves can only be rendered visible by it, either, as first described by Toepler, by illuminating the observed wave for a very short time by means of a spark produced at the right moment, or by observing the phenomenon stroboscopically. Fig. 58 (a) shows one of the first photographs made by Toepler (464) of a sound wave produced by a spark. The extraordinary accuracy of this simple striation method is seen from fig. 58 (b), due to Foley and Souder (146), who somewhat improved Toepler's original arrangement. The sound wave is produced in this case also by a spark, and proceeds to the left against a semicircular reflector, which has in it a number of openings at equal distances. We can see clearly both the elementary waves going through these openings as well as those

reflected, and also the sound wave proceeding undisturbed to the right in the form of a spherical wave.

Tawil (458) used the striation method to render travelling ultrasonic waves in air visible by forming an image of a brightly illuminated slit by means of a concave mirror on a wire of suitable thickness, so that an eye or telescope behind the wire received no light. If the sound waves now pass through the beam of light coming from the mirror, a bright band is seen on the dark background of the mirror, but if the arrangement is so adjusted



(a)



(b)

FIG. 58. Photographs by the striation method of a sound wave sent out by a condenser spark, (a) free propagation, (b) propagation through a circular diaphragm with holes.

that the sound waves simultaneously pass also through the light coming to the mirror from the slit, the band of light is seen to be interrupted by dark lines, the distance apart of which changes with the frequency of the sound. In this case the light is given a stroboscopic character by its first passage through the sound waves. Bär (24) recently investigated this phenomenon more fully (see also Chapter V (a)).

The observation of travelling sound waves by the striation method may, however, be better carried by a proper stroboscopic illumination, as, for example, by interrupting the light entering the slit *S* in fig. 55 by means of a Kerr cell system driven by the same alternating voltage as that used to drive the quartz source of sound.

Bergmann (47, 49) rendered travelling ultrasonic waves in a liquid visible on a screen by the striation method, by forming

an image of the sound waves *via* a rotating mirror, as shown diagrammatically in fig. 59, the letters of which have the same significance as in fig. 55. The travelling wave produced in the trough  $T$  by the quartz tube—formation of stationary waves being prevented by the sound-absorbing material  $A$ —is projected by the objective  $O$  on the screen *via* the rotating mirror  $R$ , the sense of rotation of which is so chosen that the image of the sound wave on the screen moves in the opposite direction to the direction of motion of the waves in the image. When the speed and direction of rotation of the mirror are correct, we see on the screen stationary dark and light bands, forming a picture of the compression and expansion places in the liquid traversed by the sound wave. If  $g$  represents the distance of the objective

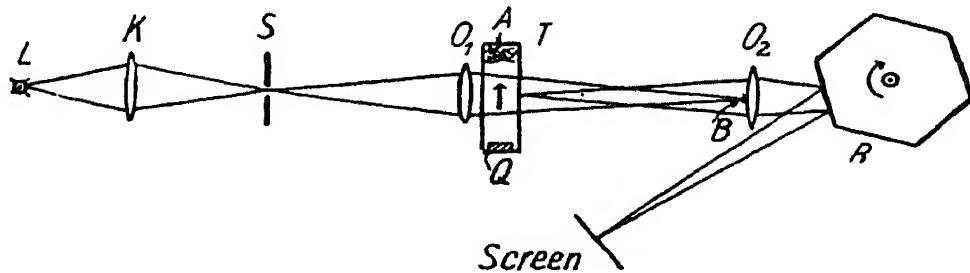


FIG. 59. Arrangement for rendering visible travelling sound waves by method of striation and rotating mirror wheel (Bergmann).

$O_2$  from the trough, and  $b$  the optical distance of the screen from the same objective  $O_2$ , and if the position of the rotating mirror is such that the distance of its surface from  $O_2$  is equal to the distance of it from the axis of rotation, we have the relation  $v_t = v_s g/b$ , where  $v_t$  is the velocity of sound in the liquid in the trough, and  $v_s$  the velocity of sound in the image on the screen. If, on the other hand,  $z$  is the number of turns of the mirror in a minute, we have

$$v_b = \frac{2 \times 2\pi \times b \times z}{60} = \frac{\pi b z}{15},$$

if we denote by  $v_b$  the rate of motion, produced by the rotation of the mirror, of the image on the screen. When the image of the sound waves is standing still on the screen,  $v_b$  must be equal to  $v_s$ , and we get

$$v_t = \frac{\pi g z}{15}.$$

We see from the last equation that, besides the number of turns

of the mirror, only the distance  $g$  enters into the determination of  $v_t$ . The larger  $g$  is made the less the number of turns of the mirror necessary. If, for example, we take  $g = 3$  m, we get for the range of sound velocities in liquids with which we are concerned, namely  $v = 900$  to  $1800$  m/s, a rate for the mirror of  $= 1500$  to  $3000$  revolutions per minute, which may be measured in various ways—for example, electrically by means of a bridge—with an accuracy of  $0.1\%$ , so that equally great accuracy in the determination of the velocity of sound may be attained. We have the further great advantage that the measurement is independent of the frequency of the sound.

**2. The Diffraction of Light by Ultrasonic Waves.** In the year 1932 Debye and Sears (122, 127) and also Lucas and Biquard (298 to 301) showed independently of one another that diffraction of light occurs in a liquid traversed by sound waves, and that diffraction phenomena quite similar to those produced by an ordinary optical ruled grating may be observed. These experiments, which have led to a great number of new methods being developed in ultrasonics, were suggested by a theory given by Brillouin (102) of the dispersion of light and X-rays in homogeneous bodies, taking account of heat motion. The latter, as is well known, may be represented as a system of elastic waves, at which a Bragg reflection of light takes place. It was therefore to be expected that diffraction of light would also take place at artificial elastic waves in a liquid. The experimental arrangement used by the above

investigators is given diagrammatically in fig. 60. A slit  $Sp$  is strongly illuminated through the condenser  $K$  by a light source  $L$ . The light proceeding from the slit is

rendered parallel by the lens  $O_1$ , and passes through the trough right angles to the sound waves in it. The second lens  $O_2$  forms an image on the screen of the slit  $S$ . When white light is used, we get on the screen, in addition to the central image of the slit, very intense diffraction spectra, up to high orders; if monochromatic light is used, we get in place of spectra sharp diffraction images of the slit. Some photographs of this sort

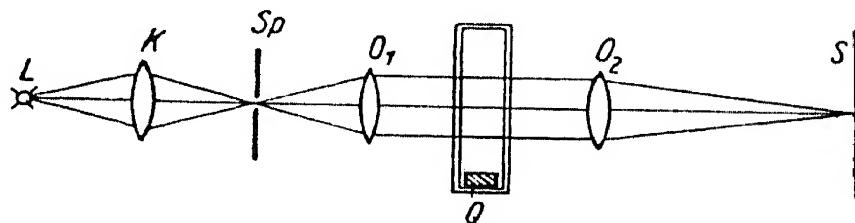


FIG. 60. Optical arrangement for diffraction of light by ultrasonics.

are shown in fig. 61, and in them we are able clearly to see the high order and great sharpness of the diffraction images.

The ultrasonic wave passing through a liquid is, as we know, an elastic wave, in which compressions and expansions travel

one behind the other at regular distances apart. The distance between two successive compressions is the wave-length of the sound in the liquid. We are thus dealing with a liquid with a density changing periodically in the direction of the sound wave, and hence also having a periodically variable index of refraction, which produces diffraction of light according to the same fundamental laws as an optical grating. If  $\Lambda$  denotes the wave-length of sound in a liquid,  $\lambda$  the wave-length of light, and  $a_k$  the angle of diffraction for the  $k$ -th order, we get the equation

$$\sin a_k = k\lambda/\Lambda.$$

If  $A$  is the distance of the screen from the sound waves producing diffraction, and  $d_k$  the distance of the  $k$ -th diffraction image from the central image, we have as the commonest case,  $A$  large compared with  $d_k$ , when we may replace  $\sin a$  by  $d/A$ , and we then get

$$d_k = kA\lambda/\Lambda.$$

A decrease of wave-length of the sound, as, say, by an increase in its frequency, thus results in a greater distance of the diffraction image from the central image. Fig. 61 shows three photographs, (a), (b), and (c), made with sound waves in xylol, using the fundamental and third and fifth overtones of a quartz plate. The distances apart of the diffraction images in (b) and (c) are accordingly three and five times greater respectively than those in (a). Since these distances and also the distance  $A$  may be measured very accurately, and since the wave-length of the light is also known, we have a very accurate method of measuring the wave-length of the sound, and hence also the velocity of sound in the liquid; in the latter case the frequency of the sound

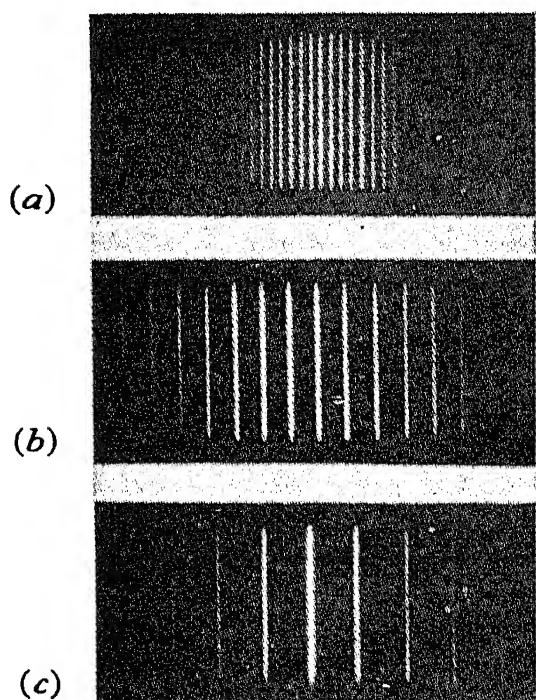


FIG. 61. Diffraction spectra of sound waves in xylol; fundamental, and 3rd and 5th harmonic.

must be known ; it may be determined by an electrical measurement of the quartz frequency. If we denote the sound frequency by  $N$  and the sound velocity by  $v$ , the above formula may be transformed into the following form, which is convenient for velocity measurements :

$$v = \frac{kA\lambda N}{d_k} = \frac{3 \cdot 10^8 kA\lambda}{d_k \lambda_{\text{elect}}^{[m]}},$$

here  $\lambda_{\text{elect}}^{[m]}$  represents the electrical wave-length of the oscillation used to excite the quartz. If the quartz is excited in several frequencies at the same time, for example in the fundamental and the overtone, or simultaneously in two different overtones, several sound waves are produced in the quartz, which produce spectra at different distances apart corresponding to their wave-length. Experiments of this sort were carried out by Bergmann (44) ; some of his photographs are given in fig. 62. In the first photograph the quartz is vibrating only in the fundamental  $N = 2548$  kHz, in the second photograph only with frequency  $3N$ . Photograph 3 shows the diffraction effect when the quartz is excited both in the fundamental and in the third overtone. Alongside each diffraction spectrum on photograph 2, we give lines at the same distance apart as the fundamental in photograph 1.

The further photographs 4 to 9 are readily understood on the same lines. Photographs of diffraction images made in this way allow us to see whether the quartz is vibrating in one frequency only, or in several. Parthasarathy (350) made similar observations, and found from diffraction pictures that a

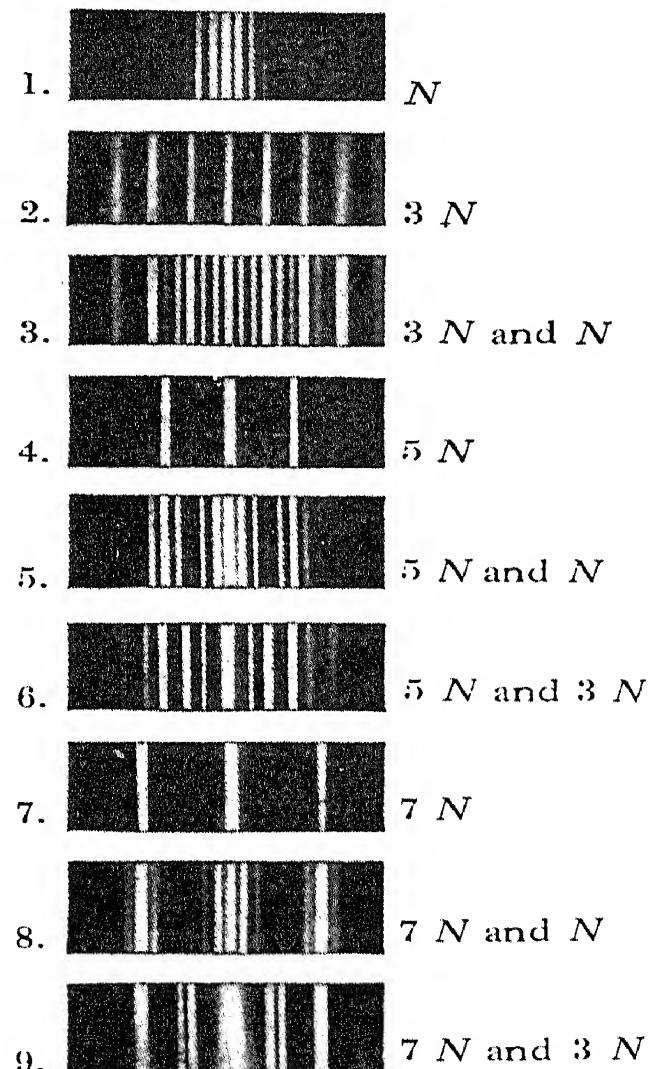


FIG. 62. Optical diffraction images of sound waves in xylol, the quartz being in vibration in a number of frequencies at the same time (Bergmann).

quartz plate may vibrate simultaneously in the 5/2 and 7/2 harmonics. Bergmann (42 to 44) drew attention to the use of optical diffraction by ultrasonics as a means of determining the overtones of a quartz, and of measuring electrical frequency, and has recently described a precision wave meter based on this principle (46).

The well-known phenomenon of the 'pulling' (*Ziehen*) of a vibrating piezoquartz out of its proper frequency may be exhibited to an audience by means of the resulting changes in diffraction effect as described by Hiedemann and Asbach (203).

It is important that this method of making ultrasonic waves visible indirectly by diffraction may be applied both to travelling and to stationary waves. In the first case the sound-waves diffraction grating is moving with the velocity of sound at right angles to the direction of the light. The consequence of this is that, owing to a Doppler effect, the light which is bent aside in the diffraction spectra in the direction of propagation of sound suffers an increase in frequency, while the light diffracted in the opposite direction is lowered in frequency. The frequency  $\nu_k$  of the light diffracted through the angle  $\alpha_k$  from its original direction may be calculated from the relation

$$\nu_k = \nu_0 \left( 1 \pm 2 \frac{nv}{c} \sin \frac{\alpha_k}{2} \right),$$

where  $\nu_0$  is the frequency of the entrant light,  $n$  the index of refraction of the liquid,  $c$  the velocity of light in a vacuum, and

$v$  the velocity of sound. Then since  $\sin \frac{\alpha_k}{2} = \frac{k \lambda}{2 \Lambda}$ , we get

$$\nu_k = \nu_0 \pm kN \text{ where } N \text{ denotes the frequency of the sound.}$$

The Doppler effect in the diffracted light is very slight on account of the very small velocity of sound as compared with that of light; it was first detected experimentally by Debye, Sack, and Coulon (126) in the following manner.\* If we screen off from the diffraction picture the central image, and all others excepting the spectra of the first order left and right, and then bring about interference between these two, the light intensity

\* For the optical wave-length of the green mercury line ( $\lambda = 5460 \text{ \AA}$ ) and for an ultrasonic frequency of  $10^7 \text{ Hz}$ , we get, for example, in the diffraction spectrum of the first order a change of wave-length of only  $10^{-4} \text{ \AA}$ .

a point varies periodically with double the sound frequency; other words, at any point in the field of view  $2N$  interference bands pass by in a second. If the light entering the sound wave interrupted stroboscopically, say by a Kerr cell, with this frequency  $2N$ , the bands seem to be brought to a standstill, and we get a system of interference bands which may be regarded as an indirect proof of the change of frequency of the light in the two spectra. The Doppler effect in spectra of higher orders may be exhibited in exactly the same way. Ali (4) has recently made a direct measurement of this change of frequency of light when diffracted by travelling ultrasonic waves, by means of the alnikowski-Schein \* method of magnetically distorting the mercury resonance line, by which it is possible to detect changes in wave-length of  $10^{-6}$  Å. The experimental arrangement is as follows: the ultrasonic wave is illuminated by light from the mercury resonance line ( $\lambda = 2537$  Å). The change in wavelength caused by the Doppler effect then results in a decreased absorption of the light in a vessel filled with mercury vapour. This change in absorption is compared with a change in the absorption of the unchanged mercury line produced by distorting the line magnetically by the Zeeman effect, the amount of which may be calculated. With a sound frequency of 7600 Hz, Ali was able to confirm the Doppler effect of  $1.6 \times 10^{-5}$  Å, calculated theoretically, as regards order of magnitude.

The conditions for the diffraction of light by stationary sound waves are somewhat different. If we regard the stationary waves as formed by the superposition of two wave trains travelling in opposite directions, we see that the diffraction image of the  $h$  order must contain the light frequencies  $\nu_h = \nu_0 \pm kN$ . Hence if we apply the above-described arrangement used by Debye, Sack, and Coulton to a stationary sound wave, we should

without stroboscopic illumination a system of interference bands, when the light of two interference images of the same order is superimposed, since they are coherent. Debye, Sack, and Coulon (126) have shown that this is actually the case; they also pointed out that this system of bands is an image of the sound wave which produces the diffraction images used. Debye has made extensive experiments in this direction. Fig. 63 shows three photographs of the kind, obtained by cutting out,

See, for example, B. M. Schein, *Helv. Phys. Acta*, 2, Suppl. I, 1929.

in the case of (a) all light other than the two diffraction images of the first order, in (b) all but that from those of the second order,

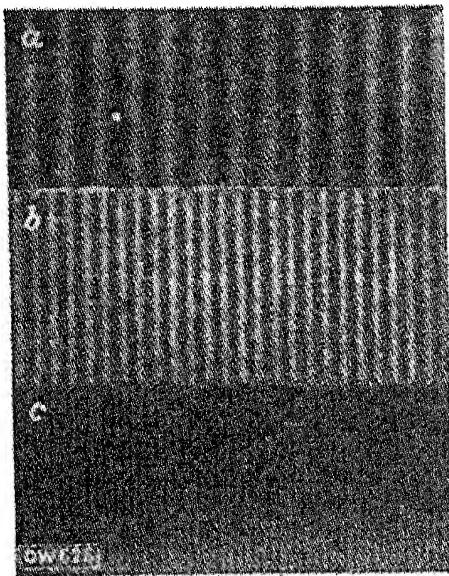


FIG. 63. Photograph of a stationary sound wave in xylol, rendered visible by means of secondary interferences (Bär).

stationary waves, such as is also required by Abbe's theory of image formation by the microscope.\*

This formation of a picture of the stationary sound waves is identical with the one obtained by the striation method, fig. 57, p. 60. If the light of zero order is also admitted, the effect is not seriously altered, for this light has no other effect than to increase the general illumination of the field. Bachem, Hiedemann, and Asbach (7, 12, 13) were the first to produce pictures of stationary ultrasonic waves in liquids in this form, and Bachem (8) also made visible travelling waves in the same manner, using intermittent illumination. Details of this are given in Chapter III, p. 58. Here we will only point out that this method may be used to render visible the form of the sound waves emitted by the surface of a vibrating quartz. As first shown by Bär (23), and later by Hiedemann and Hoesch (214), the departure of the vibration of piezoelectric quartz plates from the motion of a flat piston may be recognized by this means.

We will now once more consider the stationary sound wave

\* See R. W. Wood, *Physical Optics*, p. 223 (New York, 1911); *Dictionary of Applied Physics*, IV, p. 235 (London, 1923).

and in (c) from the third order. We see at once that in (b) and (c) the distance apart of the bands is reduced to one-half and one-third respectively as compared with (a), where the distance apart of the bands is  $f \frac{\Lambda}{2}$ , where  $f$  denotes the linear optical magnification. If we superimpose the light of all  $2k$  diffraction spectra, we have an interference picture resulting from the addition of the intensities of the  $k$  images produced by the  $k$  pairs of diffraction spectra. In this case the bright bands are considerably sharper than in 63 (a) and we get a true picture of the

liquid. Bachem (11) was doubtless the first to point out a change in frequency of the diffracted light may also come in another way. The stationary sound wave is formed disappears once in every half-period of the sound frequency.

64 shows this process graphically ; the distribution of the velocity  $v$  of the liquid particles, the pressure distribution  $p$ , the index of refraction  $n$  of the liquid are plotted against distance from the reflecting wall, both for a time  $t$ , in which formation of the standing wave reaches a maximum, and the time  $t + \tau/2$  ( $\tau$  = time period of sound wave) ; the direction of motion of the liquid particles is indicated by arrows. Between

the two states, that is within the time  $\frac{\tau}{2}$ , there must be one

instant when, over the whole range,  $v = 0$ ,  $p = 0$ , and  $n = \text{const.}$ , is to say, when there is no sound wave and hence no diffraction grating. The distance between two points having maximum index of refraction is the grating constant, and that is, as we easily see, the wave-length  $\Lambda$  of the sound. We may draw this point special attention to the fact that we have here, in case also of stationary sound waves, a diffraction grating with the whole wave-length of the sound as its constant. It is however worthy of note that the position of this grating moves and from continuously by the amount  $\frac{\Lambda}{2}$ . For example, fig. 64

shows the diffraction grating moved to the right by  $\frac{\Lambda}{2}$  at a time  $\tau/2$ ,

as we see from the curve for  $n$ . It is readily seen that velocity of displacement has its smallest value at the moment the grating is best formed; on the other hand, its greatest value when the grating is going through vanishing point. This is the reason why it is possible to see the grating, say by the diffraction method, directly in the case of stationary waves, and

are then looking at a grating with the apparent constant  $\frac{\Lambda}{2}$ .

Other words, only the momentary optical condition of the liquid is concerned in the grating effect of the sound waves, and it is the optical qualities of the liquid averaged over time which are decisive for our seeing the grating.

The periodic generation and disappearance of the sound-

wave grating in the stationary wave causes the whole diffraction effect to oscillate with the same frequency  $2N$ . This means that the light used for diffraction is modulated with the frequency  $2N$ . A series of practical applications of this modulation of light by stationary ultrasonics will be discussed in Chapter V (a). Here we may first of all notice the fact that the light modulation will cause the two frequencies  $\nu_0 \pm 2N$  (side frequencies) to

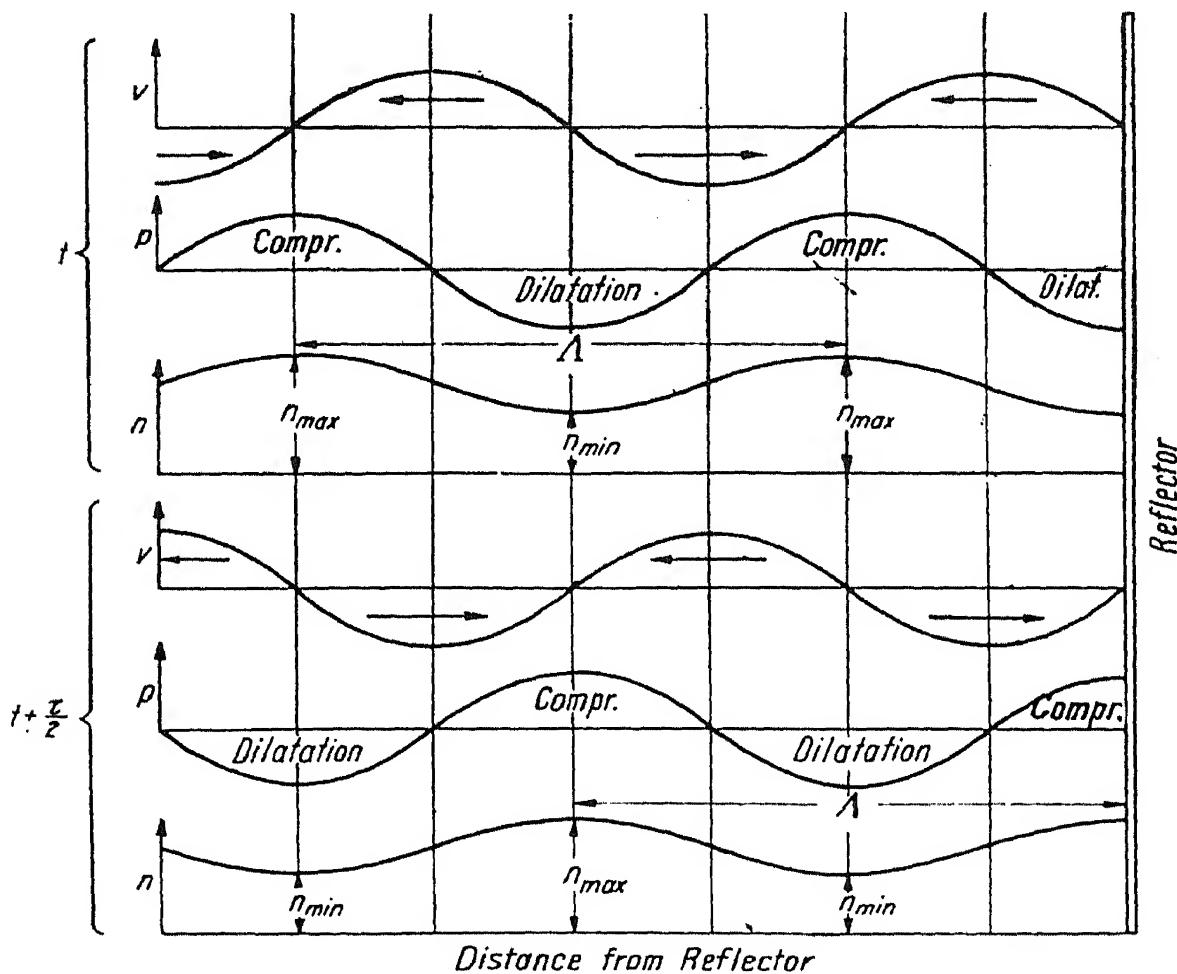


FIG. 64. Distribution of velocity  $v$ , pressure  $p$ , and refractive index  $n$  in a stationary sound wave at two instants separated by half a period.

appear in both the diffracted light and in that of zero order along with the primary light frequency  $\nu_0$  (carrier frequency); the undiffracted light also changes its intensity with frequency  $2N$ , with, however, a phase difference of  $90^\circ$  as compared with the light of the diffraction images. If we note further that the grating is moving to right and left in the liquid with the sound velocity  $v$ , or if we make the assumption, leading to the same result, that the stationary wave is made up of two travelling waves moving in opposite directions with velocity  $v$ , the light present in each diffraction image of the  $k$ -th order is subject

to a further Doppler effect of the order of  $\pm kN$  for the two light frequencies present,  $\nu_0$  and  $\nu_0 \pm 2N$ , so that the diffraction images contain light frequencies set out in the following table, the figures in brackets in this not being our concern at the moment.

We see that the images of even order ( $k = 0, 2, 4, \dots$ ) contain only the light frequencies with an even Doppler effect, while the odd spectra ( $k = 1, 3, 5, \dots$ ) show only light frequencies with odd Doppler effect. This result may be stated even more generally by making the supposition, the reasons for which will be given more fully later, that the spectra of higher order are formed by multiple diffraction, for example, by light from the spectrum of the first order being diffracted into that of the second order, and so on, while at the same time light is diffracted back again from higher orders to lower. All spectra of even order (including zero) then contain only light of frequencies  $\nu_0 \pm lN$ , where  $l$  takes on the values of all even integers between zero and  $k$ , and all spectra of odd order contain only light of frequencies  $\nu_0 \pm mN$ , where  $m$  goes through the values of all odd integers in the same interval. In this way the bracketed frequencies in Table III are produced. Bär (19) was the first to point this out, and to show by experiments that all diffraction spectra fall as regards their coherency relations into the said two groups of even and odd order numbers. All spectra of one group are at least partly coherent with one another, but any two spectra of different groups are completely incoherent.

TABLE III

*Frequencies of the Light in Diffraction Images produced by a Stationary Sound Wave*

$k$	Light Frequencies contained in the Diffraction Image of the $k$ -th Order				
0	$\nu_0$	$\nu_0 \pm 2N$	$(\nu_0 \pm 4N)$	$(\nu_0 \pm 6N)$	.....
$\pm 1$	$\nu_0 \pm N$	$\nu_0 \pm 3N$	$(\nu_0 \pm 5N)$	$(\nu_0 \pm 7N)$	.....
$\pm 2$	$\nu_0$	$\nu_0 \pm 2N$	$\nu_0 \pm 4N$	$(\nu_0 \pm 6N)$	.....
$\pm 3$	$\nu_0 \pm N$	$\nu_0 \pm 3N$	$\nu_0 \pm 5N$	$(\nu_0 \pm 7N)$	.....
$\pm 4$	$\nu_0$	$\nu_0 \pm 2N$	$\nu_0 \pm 4N$	$\nu_0 \pm 6N$	.....
$\pm 5$	$\nu_0 \pm N$	$\nu_0 \pm 3N$	$\nu_0 \pm 5N$	$\nu_0 \pm 7N$	.....

Certain points concerning the diffraction of light by ultrasonics are specially interesting, and are of great importance for the theoretical interpretation of the whole phenomenon. Firstly, it is striking that the diffraction spectra of higher order often appear in considerably greater intensity than would be expected from ordinary diffraction by ruled gratings; secondly, the distribution of intensity in spectra of the higher orders changes very irregularly when we change, for example, the direction of the incident light, or its wave-length. Debye and Sears already drew attention to the first point in their first paper (127). The elementary theory of ordinary optical gratings does not suffice to explain the phenomena, indeed, it fails already in interpreting the appearance of spectra of the second and higher orders. The sound wave causes the density of the liquid to change harmonically, and thus turns it into a medium equivalent as regards diffraction to a grating the transparency of which changes from point to point by a sine law. But such a grating should only produce diffraction images of the first order. Debye and Sears (127) at first attempted to explain the appearance of the higher orders by overtones in the quartz and in the resulting sound waves. This explanation does not succeed, since the overtones, when they are in fact present, are in general of weaker intensity than the fundamental, so that the higher spectra should not appear at anything like the observed intensity. A later theory by Brillouin (103) and Debye (123) is also unable to explain either the higher orders or the change in their distribution of intensity, so that we have no need to discuss these suggestions further.

But the idea of the multiple diffraction of light, already mentioned above in connection with the Doppler frequencies, is of essential importance; it was first put forward by Brillouin (103). If we recall the fact that light is first diffracted from zero order into the  $\pm l$  order, and that this light is then partly diffracted back from the  $\pm l$  order to the zero order, but also in part into the  $\pm 2$  order, we are able to explain, firstly, the appearance of the higher orders even in a grating with a sine-variable transparency, and secondly, the high intensity of these higher orders. But such multiple diffraction is only possible if the light traverses a sufficiently long stretch  $L$  of the ultrasonic wave field, that is to say when the ratio  $L/\Lambda$  is sufficiently

reat. This is in fact the case in most experiments. Fig. 65 \* shows two photographs taken by Bär (17) of diffraction effects. In the upper half of (b) the distance traversed by the light through the sound wave was reduced to half by the introduction of glass plates. We see early, on comparing it with (a), that the spectra of higher order are lost, and that the zero order is more intense. The following fig. 66 shows how increase in sound intensity leads to the gradual appearance of spectra of higher orders. We see also that the intensity of the diffracted light passes over to the higher order spectra, so that these become considerably brighter than the lower orders.

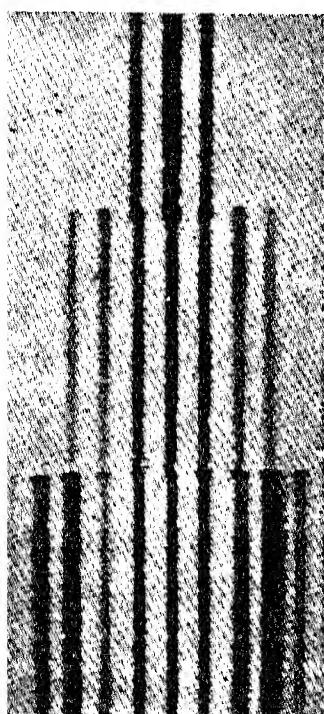


FIG. 66. Diffraction spectra of a sound wave at different sound intensities (Bär).

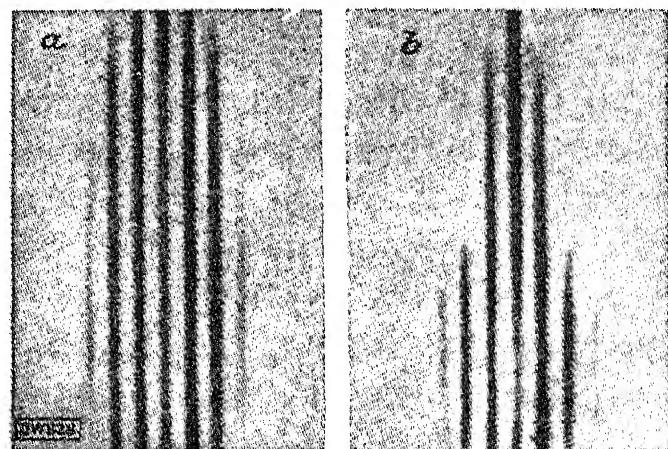


FIG. 65. Diffraction spectra of a sound wave in xylol at different thicknesses of sound wave (Bär).

Figs. 88 (b) and 89 give us a specially beautiful proof of the multiple diffraction of the light, but we can only deal with them in detail later. But we immediately recognize from fig. 88 that the light diffracted to the points of first and second order produces round these points the same circular diffraction phenomenon as is produced in the first place round the central point of the picture.

Fig. 67 shows us how the diffraction phenomenon changes when the light is not travelling at right angles to the sound wave. In (a) we have truly vertical incidence and a symmetrical diffraction picture to the right and left of the middle image, while in (b) the sound waves were turned through a small angle ( $< 1^\circ$ ), and we now recognize the appearance of unsymmetry and an increase in the intensity of zero order.

\* Figs. 65, 66, and 68 are negatives, in which the bright diffraction lines appear dark on a light ground, while the photographs of 61, 62, and 71 are positives.

Finally, the photograph of fig. 68, made by Bär, shows the dependence of the diffraction phenomenon on the wavelength of the light. The upper photograph was taken with blue light ( $\lambda \approx 4750 \text{ \AA}$ ), the lower with ultraviolet ( $\lambda \approx 3650 \text{ \AA}$ ). The difference in the intensity distribution in the higher order spectra strikes one at once. If white light is used for these diffraction experiments, the difference in the strength of the diffraction of the various wave-lengths in the higher order spectra is frequently recognizable by the fact that the middle image appears not white but coloured, and that the individual spectra show entirely different colouring. The latter

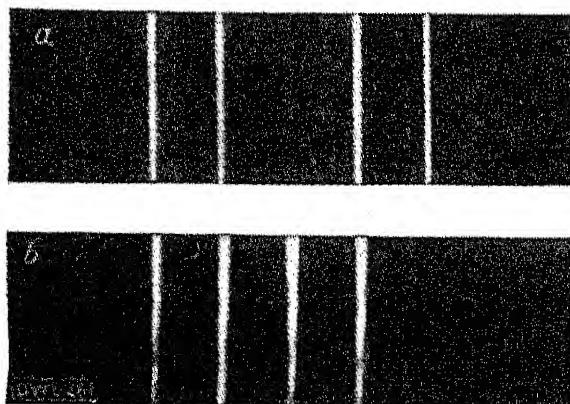


FIG. 67. Diffraction spectra with light going (a) normally, and (b) obliquely through the sound wave (Bär).

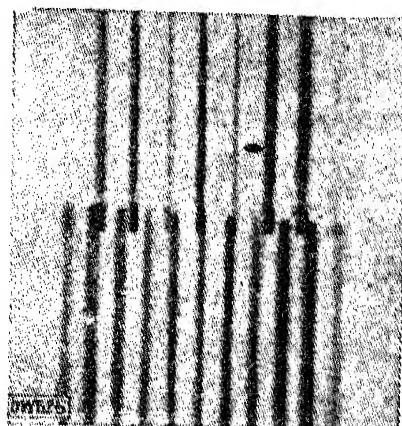


FIG. 68. Diffraction spectra of a sound wave using light of different wave-lengths (Bär).

fact may also be exhibited, for example, by throwing the whole diffraction picture on the slit of a spectroscope, setting the slit at right angles to the direction of the diffraction images. With this arrangement of 'crossed prisms' we get for each diffraction spectrum a new spectrum with different distribution of intensity. We are able in this way to determine by a single photograph the distribution of the light wave-length in all diffraction spectra produced at a given sound intensity, and also to determine it quantitatively by photometry of the photographs.

Cermak and Schoeneck (107) have recently described the appearance in the diffraction spectra of dark lines, which are always present when the light traverses the diffracting ultrasonic wave twice. This is rendered possible, for example, in an arrangement described by Pohlmann (see p. 59), by throwing

the light back on itself by means of a mirror after its passage through the sound wave. The distance apart of the dark bands is proportional to the grating consonant, and inversely proportional to the distance of the mirror from the diffracting ultrasonic grating. Dark bands of this sort in diffraction spectra may also be produced by ordinary line gratings, when two completely similar gratings are employed, or when the second is produced by a mirror image of the first. Experiments of this sort were also shown by Cermak and Schoeneck. From this it appears that we are dealing with the system of bands already observed by Quetelet (369) and fully investigated by Lommel (292). Bär (24 a) has recently given a theoretical explanation of the dark bands in the diffraction of spectra without mentioning these earlier experiments. Bär also treats the different special cases, when the two sound waves diffracting the light travel in the same (1) and in the opposite direction (2), and when they consist of one stationary and one travelling wave (3), or two stationary waves (4). On account of the Doppler effects discussed on p. 66 and occurring in the light frequencies, the dark bands appear only in cases 1 and 4, but not in case 2 and only completely in case 3.

It was a great achievement on the part of Raman and Nagendra Nath (372, 373) when they succeeded in clearing up the greater part of these phenomena, some of which are very complex, in several of their publications, though they were obliged to neglect or simplify a number of points. Thus the authors in their first paper assume that the light waves, in passing through the ultrasonic wave, are not bent or deflected, so that in passing the compression or expansion positions only the velocity and hence the phase, but not the amplitude of the light, is changed. Hence if a plane light wave passes through a plane sound wave at right angles to its direction of propagation, the sound wave acts on the light like a phase grating. In the plane of emergence of the sound wave, the amplitude of the light wave is everywhere constant, while the phase forms a periodic positional function with the sound wave-length as periodicity range. This removes the difficulty of explaining the appearance of diffraction spectra of higher orders, for a phase grating, represented in optics by an echelon grating, gives us, as opposed to an amplitude or line grating, the higher orders of spectra even when the phase changes

follow a sine law ; the intensities of the higher orders may also be calculated. Raman and Nagendra Nath thus find that the relationship of the intensities of the  $m$ -th order to the  $n$ -th order for diffraction of light by travelling sound waves may be represented by the relation  $\frac{J_m^2(a)}{J_n^2(a)}$ , where  $a = \frac{2\pi\Delta nl}{\lambda}$ , and  $J_m$  and  $J_n$  are Bessel functions of the  $m$ -th and  $n$ -th orders respectively.  $\Delta n$  gives the maximum change of refractive index of the liquid,

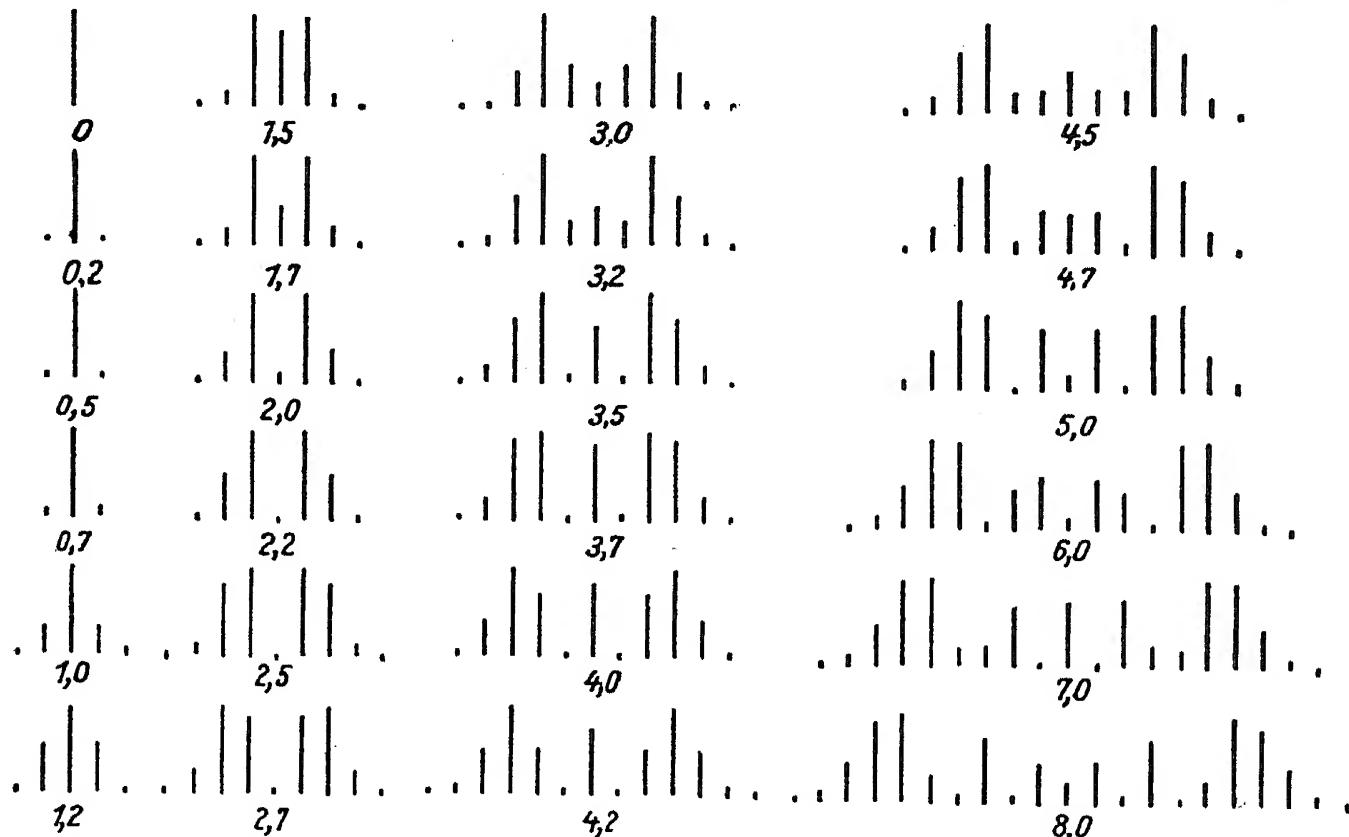


FIG. 69. Distribution of light intensity in the different orders of diffraction in a travelling sound wave as depending on  $a = \frac{2\pi\Delta nl}{\lambda}$  (Raman and Nagendra Nath).

$l$  the length of the path of the light in the sound wave, and  $\lambda$  the light wave-length. The experimental results described above are very well represented qualitatively by this relation. An exact quantitative confirmation of it is rendered difficult, in the first place, by the fact that the intensity of the sound wave in the liquid must be exactly determined. The intensities calculated by Raman and Nagendra Nath for 24 different values of  $a$  between 0 and 8.0 are plotted in fig. 69, from which we see very clearly the transference of intensity from the zero order into the higher orders,  $a = 0$  to  $a = 2.5$ , and thereafter the partial return of the light intensity to the zero order. Fig. 70 is another

presentation of the same relations. The dotted curves present, for a travelling sound wave, the light intensity in the different orders from *I* to *V*, expressed in percentages of the incident amount of light, and plotted against  $a$ . The solid curves will be discussed later on p. 79.

The authors take into account the case of oblique incidence of the light in a second paper (373). In this case, the beam of light after passing, for example, through a region of maximum refractive index, traverses also regions with a smaller index, again with the assumption of straight-line propagation; the reverse is true for the light rays which have previously passed through regions with small index of refraction, than vertical incidence. This results in a diminution of the phase difference, which acts as a diminution of the sound intensity. If  $\phi$  denotes the angle of incidence of the light against the sound wave front, we have to put in the formula given above for the intensity ratio of two successive

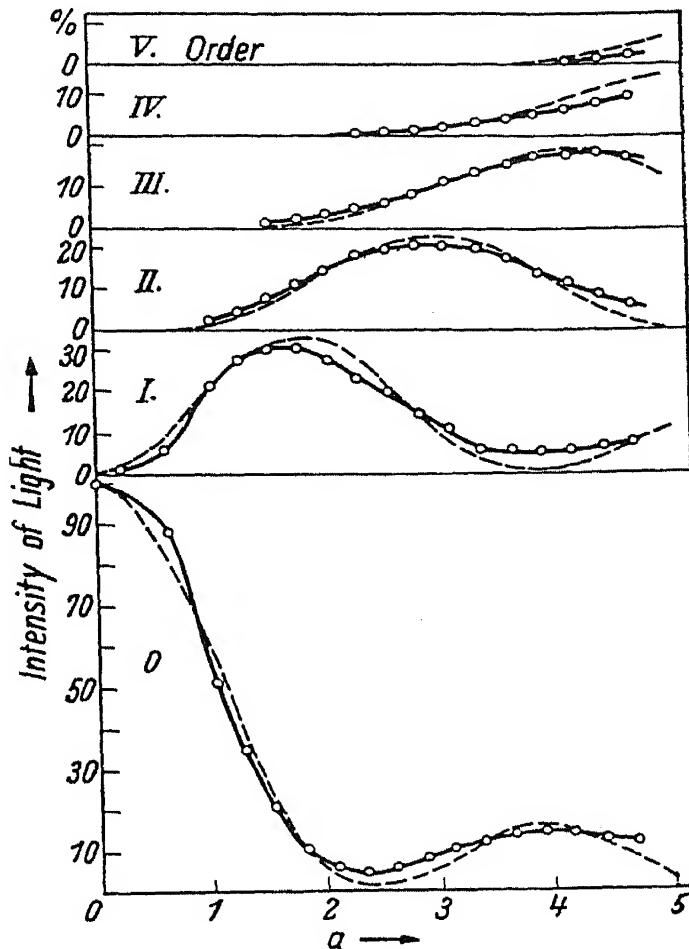


FIG. 70. Distribution of the intensity of light in the diffraction spectra of zero to 5th order in a travelling sound wave as depending on  $a = \frac{2\pi\Delta nl}{\lambda}$  (Sanders).

fraction images, the relation  $a \sec \phi - \frac{\sin \left( \frac{\pi l}{\Lambda} \tan \phi \right)}{\frac{\pi l}{\Lambda} \tan \phi}$  in place of

$$\frac{\sin \left( \frac{\pi l}{\Lambda} \tan \phi \right)}{\frac{\pi l}{\Lambda} \tan \phi}$$

and this again becomes  $a$  for  $\phi = 0$ . This gives us a series of discrete angles of incidence, at which, in agreement with the observations of Debye and Sears already described, certain diffraction spectra appear very strongly, while between them are angles at which they go through a minimum. The theory, however, requires the diffraction phenomenon to be

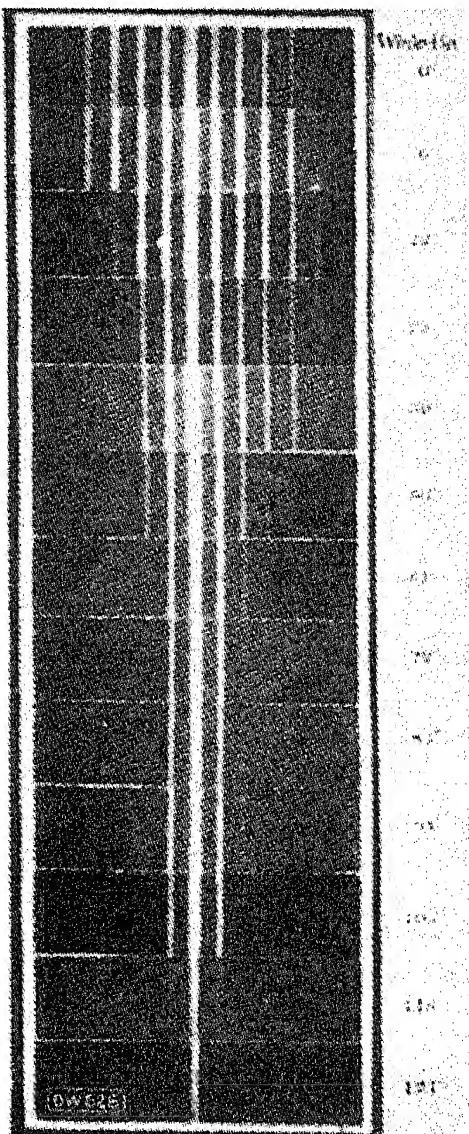
symmetrical to the incident light ray, which is never the case in the experiment; this is, for example, to be seen in fig. 67, and still more plainly in fig. 71, which gives more recent diffraction photographs taken by Parthasarathy (350) of travelling sound waves and different angles of incidence  $\phi$ .

We have the greatest unsymmetry of the diffraction images against the central image at an angle of  $22'$ , without any reduction in the total number of diffraction images. When the angle of incidence is further increased, the number of diffraction images decreases, finally disappearing almost completely at about  $2^\circ$ . The one-sided intensity distribution of the diffraction images under oblique incidence may perhaps be interpreted, according to Bär (21), by taking the light of the first order, lying nearer to the incidence vertical to be more strongly diffracted into the higher orders than that of the second order, which is more distant from the vertical.

The theory of Raman and Nagendra Nath, already mentioned, leads also to the Doppler frequencies given above both for the travelling and for the stationary wave, their correct value being given. Fig. 72 shows how the light intensities for different intensities of the stationary sound wave ( $a = 0$ ,  $a = 5$ ) are distributed among the individual Doppler frequencies in each

FIG. 71. Dependence of diffraction phenomena in a travelling sound wave upon the angle of incidence of the light (Parthasarathy).

diffraction image. If the intensities in the separate spectra are added together, we get a completely different intensity distribution from the case of the travelling wave (fig. 69). The dotted curves of fig. 73 show the calculated distribution of intensity of light in the different orders  $I$  to  $V$  plotted against  $a$ , for a stationary sound wave. The differences are plainly seen by comparison with the corresponding fig. 70 for a travelling wave. The zero



latter always comes out relatively strong, chiefly owing to the fact of the disappearance,  $2N$  times, of the diffraction effect, but the intensities of the higher orders show in general an approximately continuous decrease in intensity. This is very well seen in fig. 74, in which the total intensities of the individual

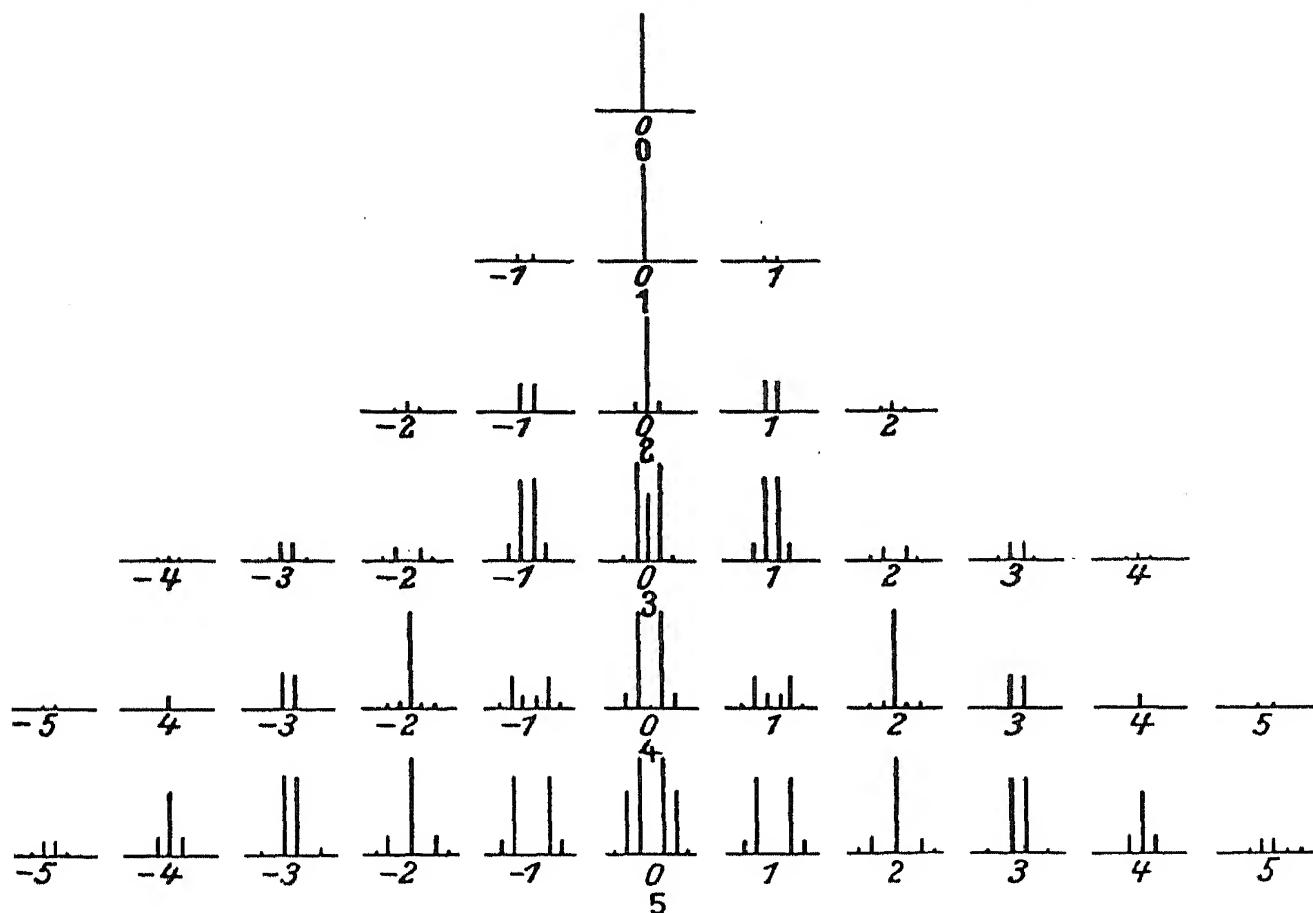


FIG. 72. Distribution of intensity of light in different orders of diffraction by a stationary sound wave as dependent on  $a = \frac{2\pi\Delta nl}{\lambda}$  (Raman and Nagendra Nath).

raction spectra are represented by Levi (288) for travelling waves for stationary sound waves,  $a$  being the same in each case; the author calculated independently of Raman and Nagendra Nath the frequency change of light when diffracted by travelling stationary ultrasonics. The full curves of figs. 70 and 72 show how well in general the Raman-Nath theory represents the facts; these curves are based on observation by Sanders (1, 405) with monochromatic light and at sound frequencies from 106 kHz to 4940 kHz. The individual points on the curves represent the mean values of the two diffraction images of the same order. It was already stated on p. 75 that the theory of Raman and Nagendra Nath, as so far described, neglects the

curvature of the light rays in the sound wave, but as a liquid traversed by a sound wave is a medium with a variable index of diffraction, a curvature of this sort must in fact be present.

Lucas and Biquard (299, 300) already calculated in their first paper the curvature and course of parallel light rays, incident at right angles to a sound wave travelling to the  $Z$  direction and of the wavelength  $\Lambda$ ; the only assumption made was that the optical condition of the liquid is not changed in the time taken by the light to pass through the sound wave. If  $\Delta n$  denotes the maximum change in the refractive index of the liquid, produced by the sound wave, this changes periodically in the  $Z$  direction according to the relation

$$n = n_0 + \Delta n \cos(2\pi z/\Lambda).$$

We then get the course of the rays given by fig. 75.\* The value

of  $K = \frac{2\pi}{\Lambda} y \sqrt{\frac{\Delta n}{n}}$ , whereby the dependence of the curvature of the light wave on the change in refractive index  $\Delta n$  is expressed. When the light emerges from the sound wave, the distribution of its intensity, though having the period of the sound wavelength, is never the less more complicated than in the case of ordinary diffraction gratings, and varies also chiefly with the thickness and intensity of the sound wave. We have to deal both with an amplitude and with a phase grating. The amplitude

\* An experiment for demonstrating such a path of light rays in a liquid is already given by R. W. Wood in his book *Physical Optics*, London, 1905, p. 74.

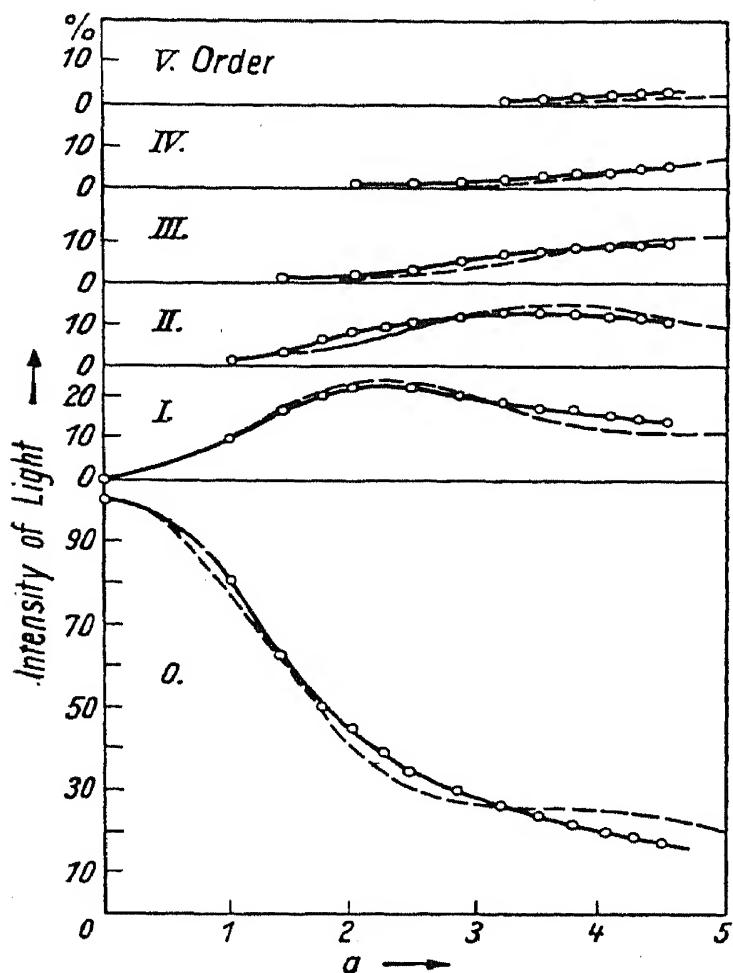


FIG. 73. Distribution of intensity of light in diffraction spectra of zero to 5th order with stationary sound waves, as depending on  $a = \frac{2\pi\Delta nl}{\lambda}$  (Sanders).

d phase of the light may be calculated, as Lucas (293) has shown, as long as  $K$  is less than 1.57—that is to say, as long as light rays cut one another in the sound wave. But if  $K$  is greater than 1.57, the light rays emerging from the sound wave appear to come from a series of lines of convergence, which lie in the liquid separated by distances equal to the sound wave-length  $\Lambda$  in the direction of the sound wave in the liquid. The distance  $y$  of the lines of convergence, in which the light rays cut one another for the first time, from the plane of

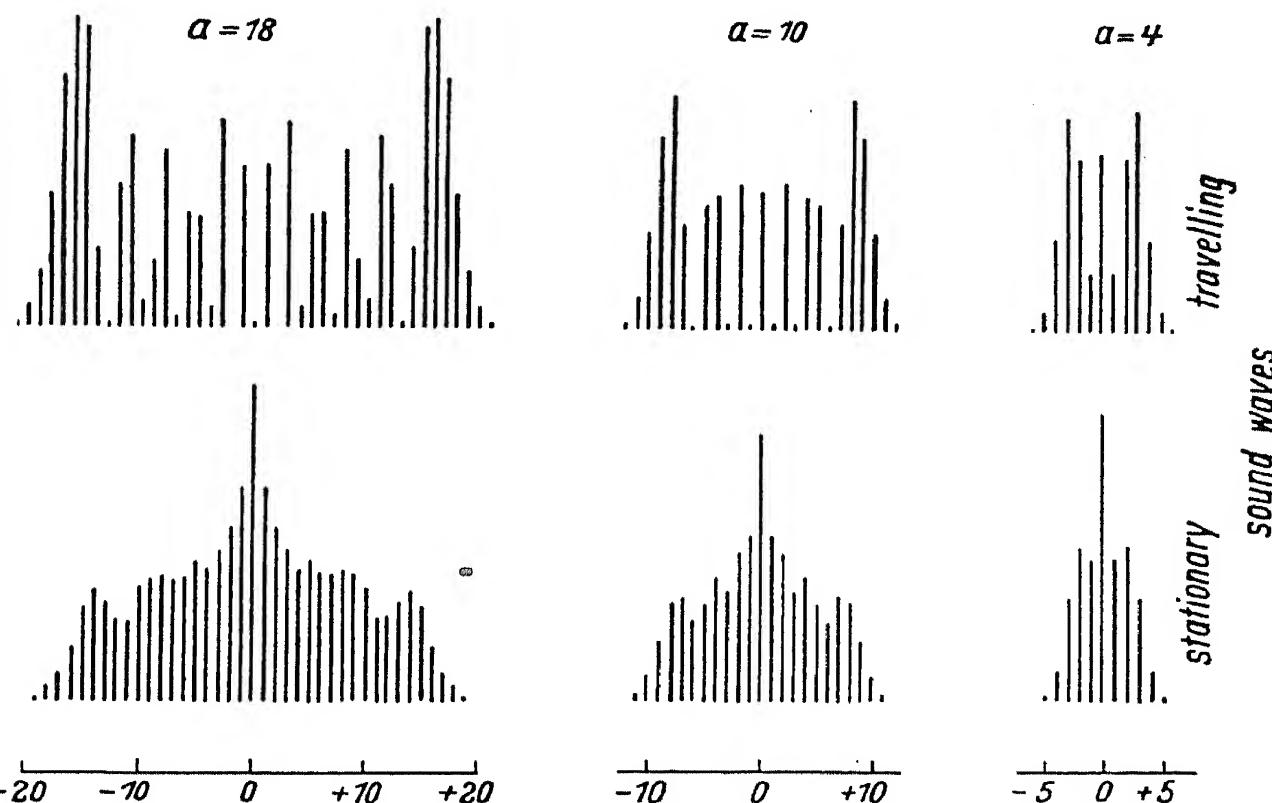


FIG. 74. Distribution of intensity in the diffraction spectra of stationary and travelling sound waves as dependent on  $a = \frac{2\pi\Delta nl}{\lambda}$  (Levi).

cidence of the light in the sound wave, is given by the relation  $= \frac{\Lambda}{2\pi} K_0 \sqrt{\frac{n_0}{\Delta n}}$ , where  $K_0 = 1.57$ . In the case of stationary sound waves the process of formation of the lines of convergence is somewhat more complicated, a matter which we will discuss further on p. 93. If we first take  $\Lambda = 0.1$  cm, corresponding to the case of water to a sound frequency of 1484 kHz, and for  $\Delta n$  the value  $10^{-5}$  ( $n_0 = 1.333$ ), which is easily attained with a moderate intensity of sound, we get  $y_0 = 9.1$  cm, while for a sound wave-length of 0.03 cm ( $N = 4948$  kHz) we have, on the

other hand,  $y_0 = 2.7$  cm only. If therefore we use in experiments on diffraction by sound waves a wave about 3 cm. deep, the light will be very considerably curved in passing through a sound wave of frequency 4948 kHz, while at the lower frequency of, for example, 1484 kHz, a noticeable curvature will not yet appear, so that in this latter case the Raman-Nath theory, in its first

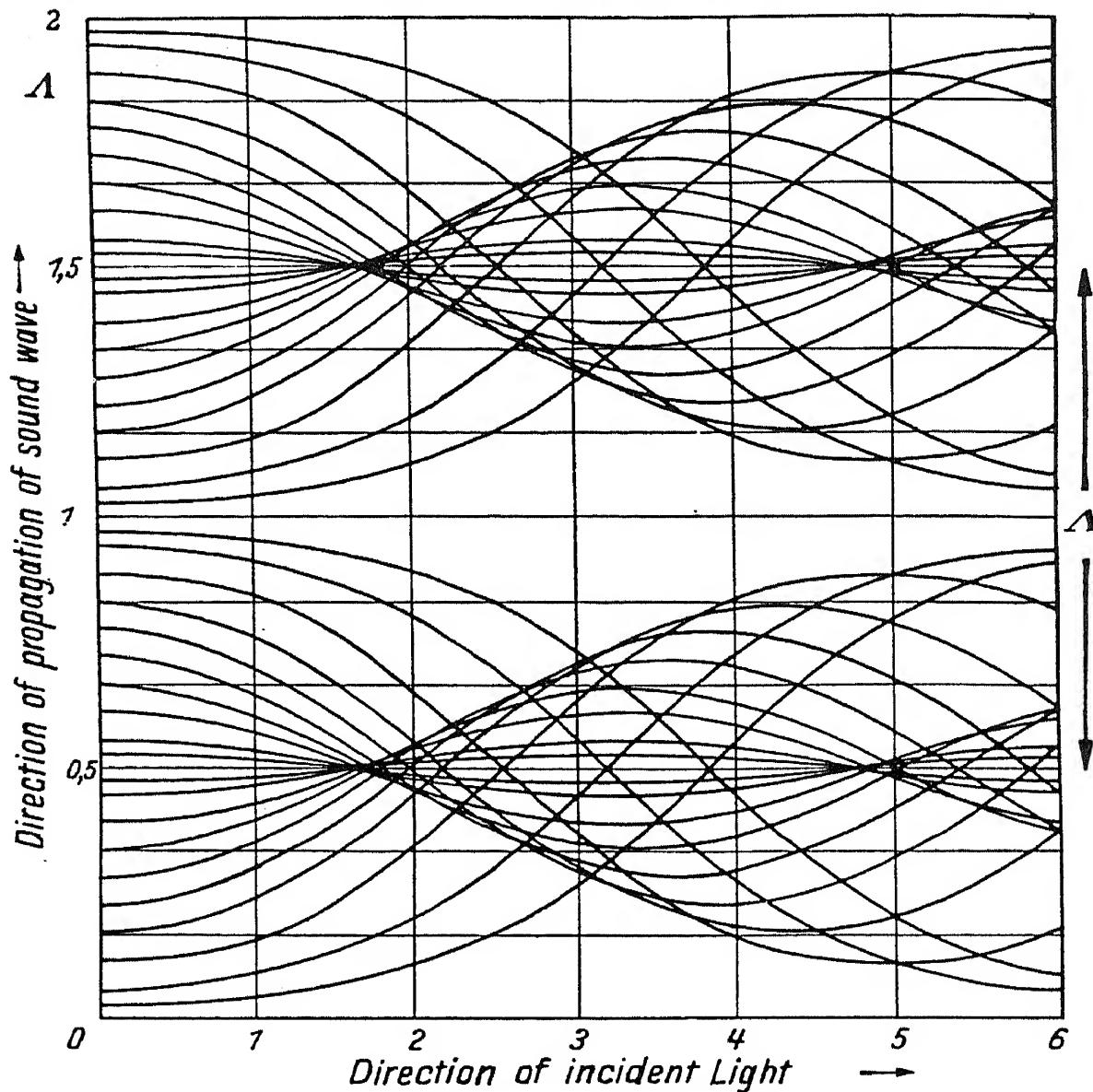


FIG. 75. Path of light rays in a medium carrying sound (Lucas and Biquard).

approximation, gives the relations correctly and almost quantitatively. Bär (21) was the first to draw attention to this set of facts, and to give as measure of the degree of approximation to the Raman-Nath theory the relation  $f = b/\Lambda$ , where  $b$  denotes the distance through which the light ray is bent from its original direction after passing through the sound wave. We find for  $b$  the relation

$$b = \frac{l^2}{R} = l^2 \frac{1}{n_0} \frac{dn}{dz},$$

where  $R$  is the radius of curvature of the light ray and  $l$  the length of the light path in the sound wave. Making use of the equation

$$n = n_0 + \Delta n \cos \frac{2\pi z}{\Lambda}$$

page 80), we get

$$b = l^2 \frac{2\pi}{n_0} \frac{\Delta n}{\Lambda}$$

and hence

$$f = l^2 \frac{2\pi}{n_0} \frac{\Delta n}{\Lambda^2}.$$

The smaller  $f$  is the smaller is the curvature of the light rays in a sound wave, and the better is the agreement with the above theory of Raman and Nath, which neglects this curvature. For the sound frequencies 1484 and 4984 kHz used in the above numerical example, we get in water with  $\Delta n = 1 \cdot 10^{-5}$  and for  $l = 3$  cm.

$$f = 4 \cdot 2 \times 10^{-2} \text{ and } 0 \cdot 7 \text{ respectively.}$$

It is to be noticed that  $f$  is inversely proportional to the wavelength of the sound.

Bär (19) has given a simple method of showing there exists in the emergence plane of the light from the sound waves an amplitude grating—that is to say, a light intensity changing periodically in the direction of the sound wave. This is done by putting on the wall of the trough in which a stationary sound wave is produced a piece of sensitive paper, or a photographic plate, whereby we are able to get, by the use of parallel light, a "print" of the ultrasonic grating. In the same way, by putting the sensitive paper in the liquid, that is to say, in the sound wave itself, we are able to convince ourselves of the gradual formation of the amplitude grating. We are not able to do this in an exact manner from outside by the use of optical methods, because the light rays after leaving the plane under investigation travel on farther through the sound waves, and experience a further change of direction (see fig. 75), so that the effect observed

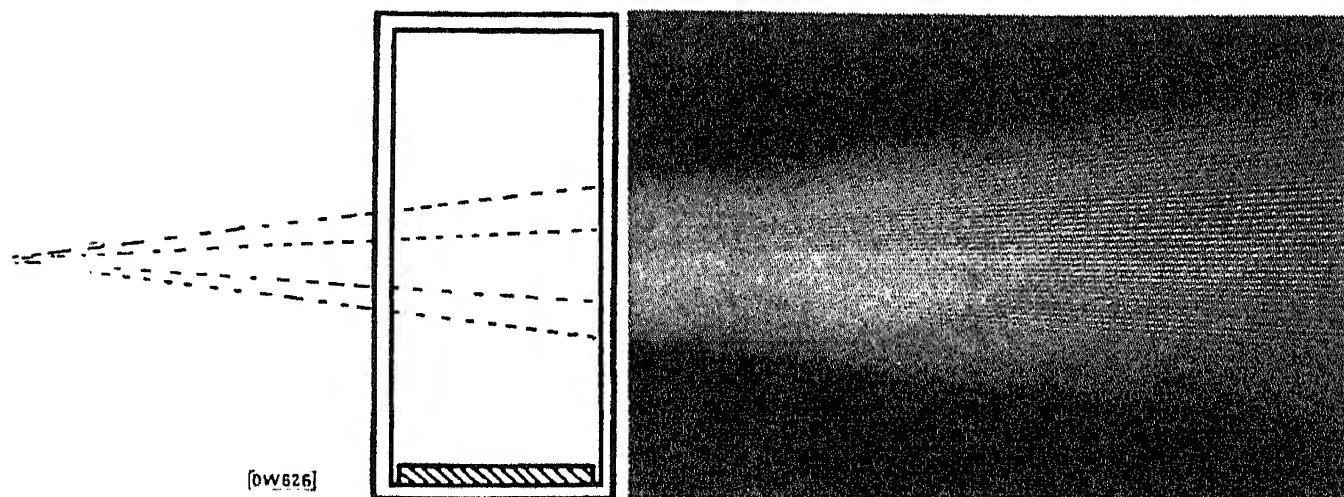
has no longer anything to do with the diffraction phenomenon in the plane considered. Bachem, Hiedemann, and Asbach (7, 8, 12, 13) have published a number of papers in which they describe a new method for rendering visible ultrasonic wave gratings in liquids, and believe that they are able to recognize directly the bright lines of convergence of the light in the liquid traversed by ultrasonics, but we shall see in the next section that we are here dealing with another process, as would appear from the discussion of these experiments. If we go over to low sound frequencies, the above considerations make it no longer possible to detect any amplitude grating in the emergence plane of the light from the sound wave. Bär (21) has shown that this is the case, for example, for a sound frequency of 1500 kHz, and he also proves that the amplitude grating only becomes visible at a certain distance from the emergence plane, possessing its best visibility at a quite definite distance, the position of which, on the other hand, depends again on the intensity of the sound wave, and approaches nearer to the sound wave the greater the sound intensity, and hence, for a given sound frequency, the curvature of the light rays. This is shown, for example, by the following table taken from Bär's papers, in which the position of the amplitude grating is given as depending on the number of the diffraction spectra observed, that is the sound intensity. This even allows of the measurement of the ultrasonic intensity by the position of the place of best visibility of the amplitude grating, a fact to which Baumgardt (29) was the first to draw attention (see p. 134).

TABLE IV

*Position of the Amplitude Grating produced by Stationary Sound Waves*

Number of Diffraction Spectra	Distance from the Position of Emergence of the Light from the Sound Wave, at which the Amplitude Grating	
	is just visible	has best visibility
1	cm 20	cm 50
2	10	25
3	3	10
5	..	2

If a stationary sound wave in a liquid is illuminated with divergent light, emitted, for example, by the straight filament of a single filament lamp, and if the emergent light is then allowed to meet a photographic plate at a slight inclination, we get, as Bergmann and Goehlich (51, 52) were able to show, a divergent bundle of sharply limited light rays, which start directly from the emergence of the light from the trough, and hence likewise gives us a proof of the existence of an amplitude grating (fig. 76). The experimental arrangement and details will be discussed more fully in the next section. This phenomenon becomes clearly marked and more blurred, the longer the wave-length.



G. 76. Passage of a divergent bundle of rays through a stationary ultrasonic wave (Bergmann and Goehlich).

the sound, in agreement with the above considerations concerning the formation of an amplitude grating.

Raman and Nagendra Nath have further developed and generalized the theory of the diffraction of light at ultrasonic waves in two further papers (374) using the wave equation for the propagation of light in the medium with spatially and temporally changing index of refraction. Simply from the spatio-temporal periodicity of the travelling and also of the stationary sound wave, we get by a Fourier analysis the correct law of diffraction, and also the correct Doppler frequencies of the diffracted light, as given above. At the same time, this theory gives us, along with the existence of a phase grating, an amplitude grating not yet given by the first approximate theory; and as a necessary consequence for oblique incidence of the light, we have unsymmetry in the distribution of the

intensities in the diffraction spectra right and left of the central image. Nagendra Nath (322) has given a solution of the differential equations, by means of the development of a series, for the case when the periodic function of the index of refraction is represented by a simple sine function. Detailed discussion of this theory, which is mathematically complicated, is outside the scope of this book. Quite recently Extermann and Wannier (142 *a*) have given a theory of the diffraction of light by travelling ultrasonics based on representing the light wave in its passage through the sound-carrying medium as the sum of a large number of plane waves. The intensities of the separate plane waves may be estimated from the boundary conditions of the problem, and then superposed.

There is one point which has still to be referred to. It was already stated above that Brillouin (103) attempted to explain the diffraction of light by ultrasonics by a selective Bragg reflection at the sound-wave fronts, as Debye and Sears also did in their first experiment. Though this leads to the same angles of diffraction, it does not explain the great intensity of the diffraction spectra of higher orders, since the reflection of light by a medium with variable index of refraction may be neglected, when the change in the index of refraction takes place gradually in comparison with the wave-length of the light. But if we turn to very small sound wave-lengths of the order of  $10^{-2}$  cm and smaller, corresponding to frequencies of the order  $10^7$  Hz, we get a correspondingly steeper gradient of the index of refraction, and a measurable reflection of the light in the Bragg sense becomes possible. Experiments of this sort with sound waves of length 0.065 and 0.05 mm were made by Parthasarathy (349), who got for certain angles of incidence intensified diffraction spectra in the direction required by the Bragg relation. With oblique incidence, we therefore have a superposition of the effect caused by propagation, and that caused by reflection of the sound-wave front, the latter only acquiring a sensible influence at high-sound frequencies. Since both effects lead to the same values for the angle of diffraction, the difficulty of separating the intensities belonging to each of the two effects in each of the diffraction spectra is increased in the quantitative treatment of the problem. Rytow (402) has also recently investigated the diffraction of light, both theoretically and practically, in the ultrasonic range

from 30,000 to 70,000 kHz, and found, at these frequencies, intensity distributions approximating closely to selective reflection under the Bragg glancing angle. The diffraction of light by ultrasonic waves in air was first detected by Bär (22), who obtained spectra up to the second order. Korff (272) carried out quantitative intensity measurements of the light diffracted by sound waves in air in the spectra of the first order, using sound frequencies of 4280 kHz and different angles of incidence of the light on the sound wave. A maximum of diffracted light was obtained when the light rays met the sound-wave front at the Bragg angle. This is readily understood from what has just been said, on account of the very short sound wave-lengths (about  $8 \times 10^{-3}$  cm) and the resulting steep gradient of the index of refraction.

We may close this section by mentioning a method given by Bär and Meyer (25, 26), which allows the diffraction of light by ultrasonics, according to Debye-Sears and Lucas-Biquard, to be used not only for proving the presence of a sound wave, but also for exhibiting its shape and path. For this purpose the image of the slit hitherto employed, which has to be parallel to the planes of the sound wave, is replaced by the images of a great number of circular apertures lying in a plane; these images being formed on a screen by light passing through the sound-wave field (fig. 77). *B* is the diaphragm with the circular apertures, formed, for example, by a card with a great number of pin holes at regular distances of 2 to 10 mm, *O*<sub>1</sub> is a condenser, giving as far as possible even illumination of the apertures, and giving an image of the lamp *L* in the plane of the objective *O*<sub>2</sub>, which produces an image of the apertures on the screen *S*. *T* is the trough containing a liquid, in which the sound wave is generated by means of the quartz *Q*. We then get on the screen diffraction spectra on both sides of those points of light, the light of which has gone through the sound wave, the line joining the diffraction spectra lying in the direction of propagation of the sound wave. We thus have on the screen a sort of picture of the whole sound

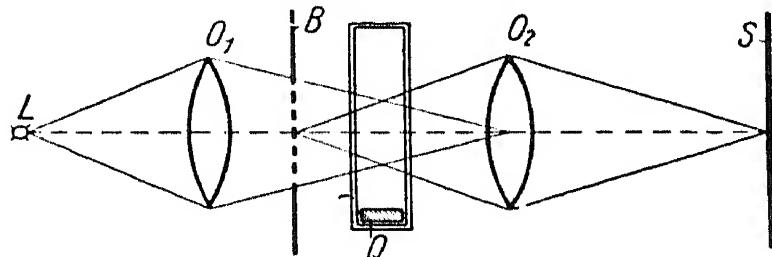


FIG. 77. Optical arrangement for making sound waves visible (Bär and Meyer).

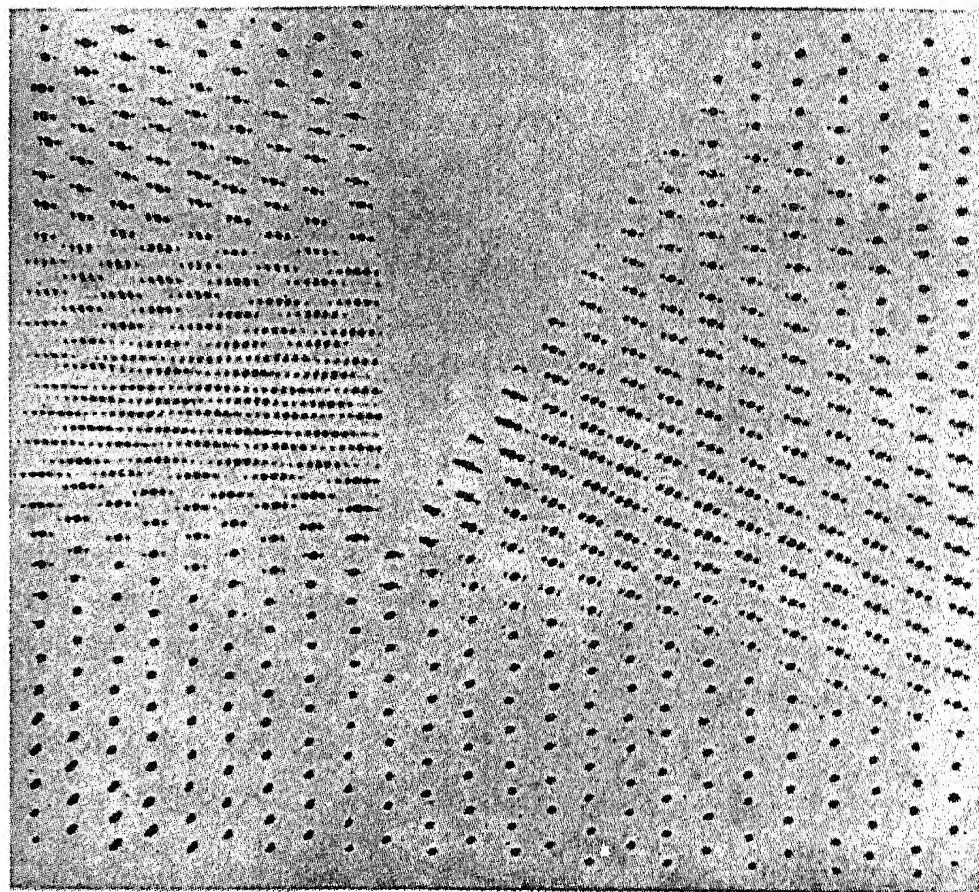


FIG. 78. Refraction of an ultrasonic wave in xylol by an aluminium prism (photographed by Bez-Bardili by the method of Bär and Meyer).

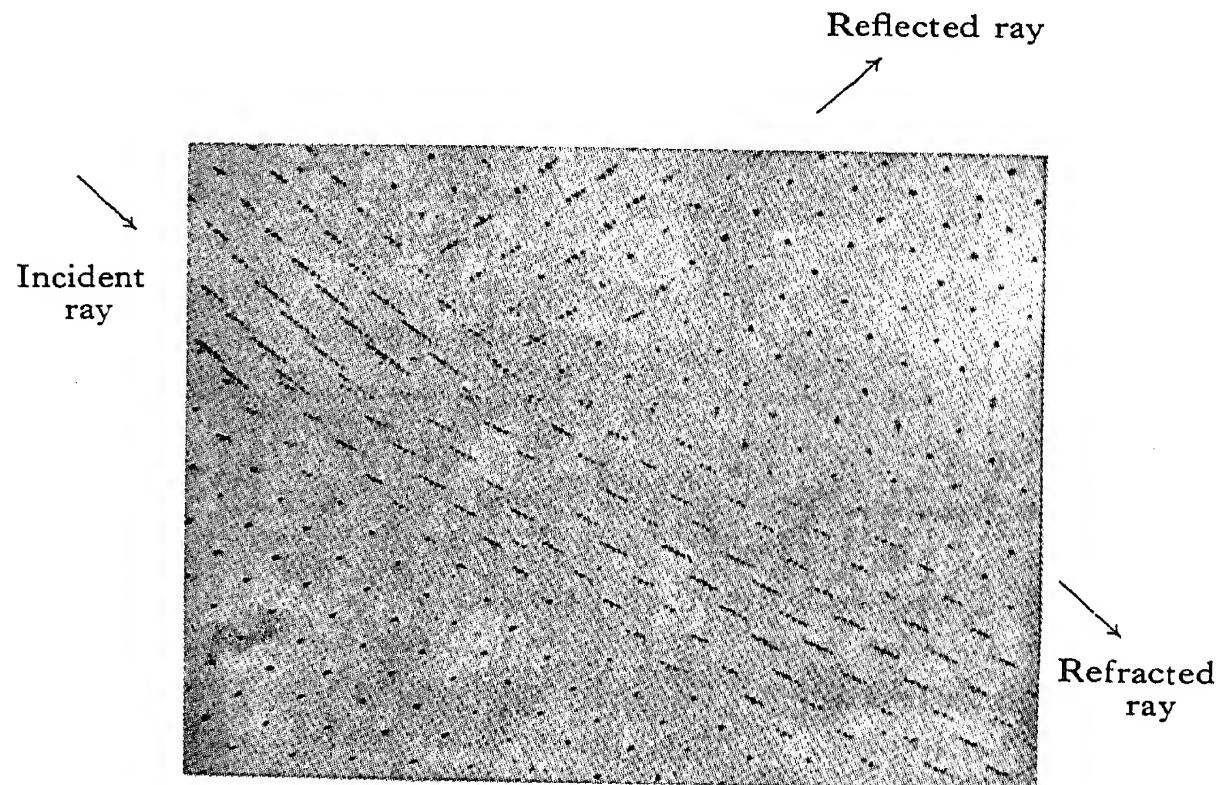


FIG. 79. Refraction and reflection of an ultrasonic ray at the boundary between xylol (top) and water (bottom), from Bär and Meyer.

wave. Fig. 78 shows a photograph of this sort, in which the sound wave coming from the left falls on an aluminium prism, by which it is refracted away from the normal, since the velocity of sound in aluminium is greater than in the liquid in the trough. The decrease in number of the diffraction spectra of the separate points of light gives us at the same time a general idea of the decrease in intensity of the sound wave, and hence of the absorption of sound in the liquid. Fig. 79 shows the case in which the sound wave enters water at an angle of  $53.5^\circ$  from xylol. We see clearly the reflected and the refracted sound ray. If the angle of refraction is measured from it, as is readily done, we are able to calculate from the coefficient of refraction the relative velocities of sound in two liquids. This experimental arrangement allows us, as Bär and Meyer (25) have likewise shown, to detect the diffraction of sound waves at a wire grating immersed in the liquid, and to determine the angle of diffraction. The constant of the wire grating being known, we have thus a further method of measuring the wave-length of sound in the liquid, and hence of determining the velocity of sound. Bez-Bardili (55) made a series of very beautiful photographs by this Bär-Meyer method, which allows a whole system of ultrasonic "optics" to be developed. Hiedemann and Asbach used this method for detecting the positions of maximum transparency for sound in a wedge-shaped plate (204), and for investigating the distribution of the amplitude of a sound wave in front of a vibrating quartz plate. Fig. 80 gives an example of the latter case.

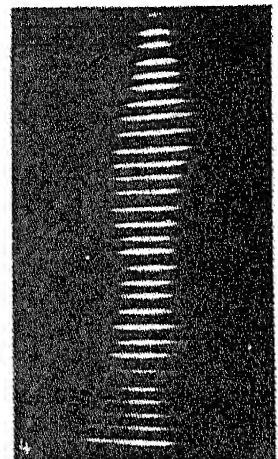


FIG. 80. Amplitude distribution of an ultrasonic ray in front of a vibrating quartz (Hiedemann and Asbach).

**3. The Method of Secondary Interferences.** Bachem, Hiedemann, and Asbach (12, 13) described at the end of 1932 a new method for making stationary ultrasonic waves directly visible, one which they at first regarded as a sort of striation method. Bachem used the same method at the same time for the observation of travelling sound waves, using an optical Kerr system for stroboscopic illumination. In their later papers (7, 207, 208) these authors interpret their experiments as rendering visible the bright lines of convergence in a sound wave, resulting from the curvature

of the parallel incident light rays according to Lucas-Biquard (as in fig. 75). Their experimental arrangement is shown in fig. 81. The light coming from the illuminated slit  $Sp$  is rendered

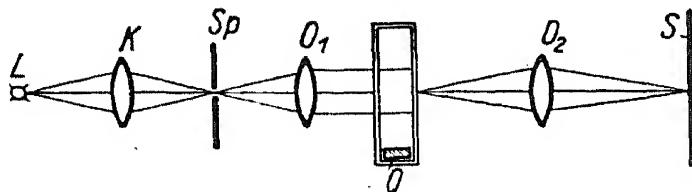
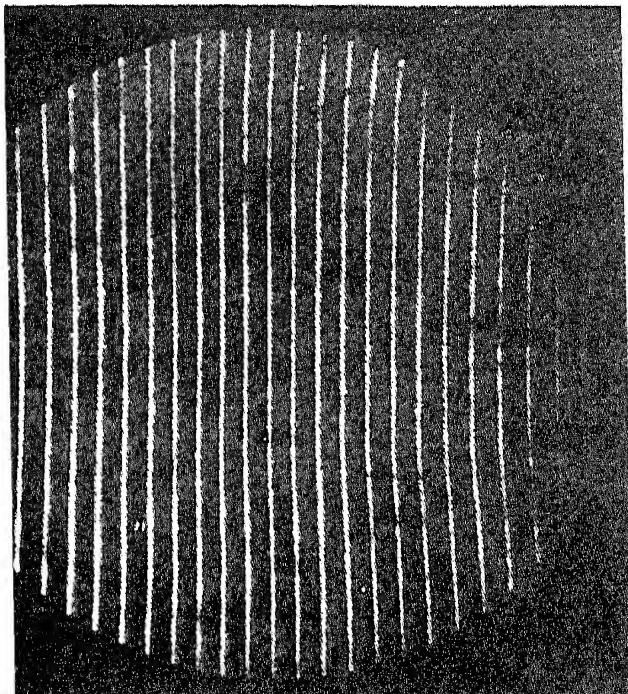


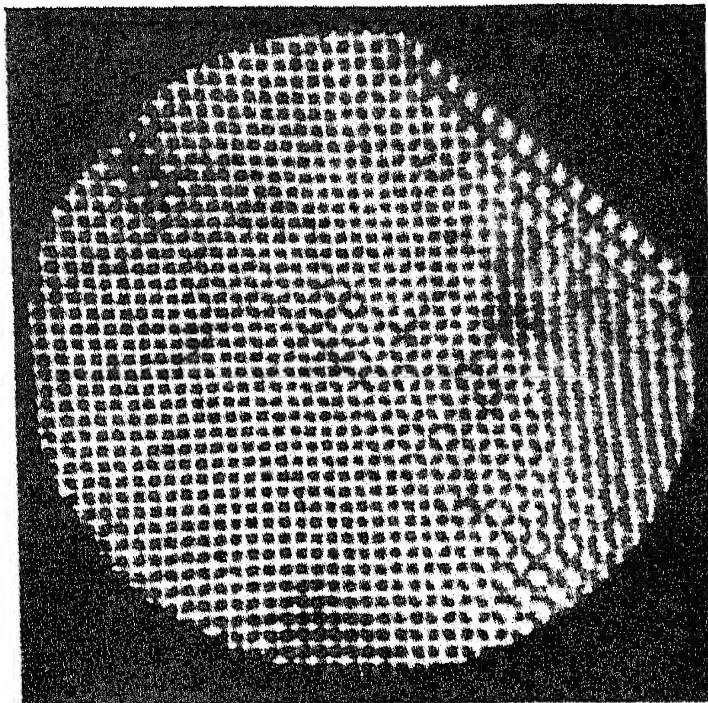
FIG. 81. Optical arrangement for rendering visible ultrasonic waves by the method of secondary interferences (Hiedemann).

parallel by the objective  $O_1$ , and traverses the sound wave produced by the quartz  $Q$ . The microscope objective  $O_2$  is focussed on a plane in the sound wave or behind it, in which the bright convergence lines are formed

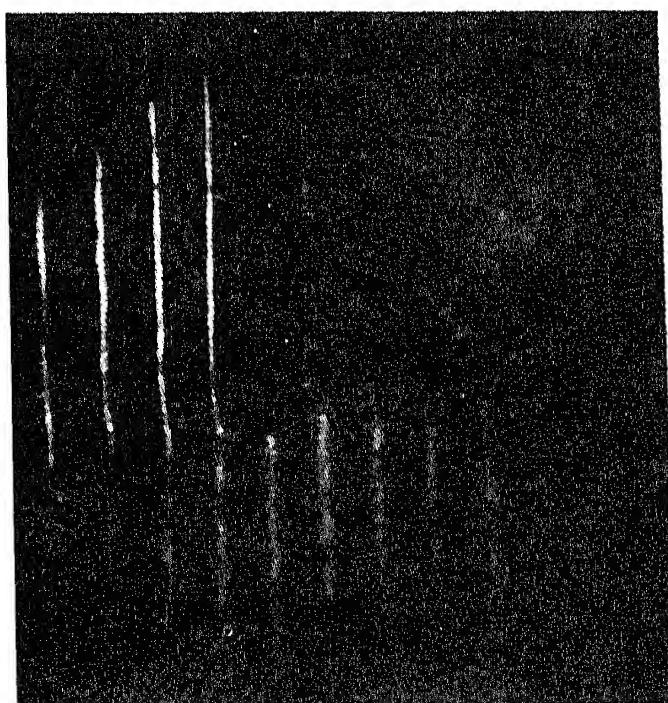
according to Lucas and Biquard. We then see either a system of bright bands, under subjective observation, or, if the light is strong enough, the bands may be projected objectively on the screen  $S$  by the objective  $O_2$ . The optical arrangement is therefore the same in essentials as that described by Debye-Sears or Lucas-Biquard and shown in fig. 60, the difference being that not the slit  $Sp$ , but a plane containing the convergence lines is seen on the screen  $S$ . By shifting  $O_2$  we are then able to go over from one experimental arrangement to the other; or, what amounts to the same thing, the screen  $S$  may be shifted when the objective  $O_2$  is correctly placed. Fig. 82 shows some photographs made in this way by Hiedemann and his co-workers of stationary and travelling ultrasonics. In fig. 82 (a) we have a plane stationary wave. In fig. 82 (b) we have a stationary wave reflected at an angle of  $45^\circ$ ; the sound wave falls, after reflection by the reflector visible in the right-hand upper corner, on the bottom of the trough, whereby a stationary wave is formed. In fig. 82 (c) we have a representation of the diffraction of a travelling sound wave at an edge, using the same method of stroboscopic illumination. The sound wave coming from the left strikes a thin steel plate, which dips into the glass cell from above. We are readily able to recognize the diffraction of the sound wave at the edge of the steel plate. Finally, fig. 82 shows the sound-wave field proceeding from the edge of a vibrating quartz at a frequency of 3005 kHz. As is well seen in fig. 82, the bright lines produced by this method in the field of view, and having in the case of a stationary wave a spacing of  $\Lambda/2$  and in the case of a travelling wave of  $\Lambda$ , are very sharp, as long as truly parallel light is used for illuminating sound waves. The



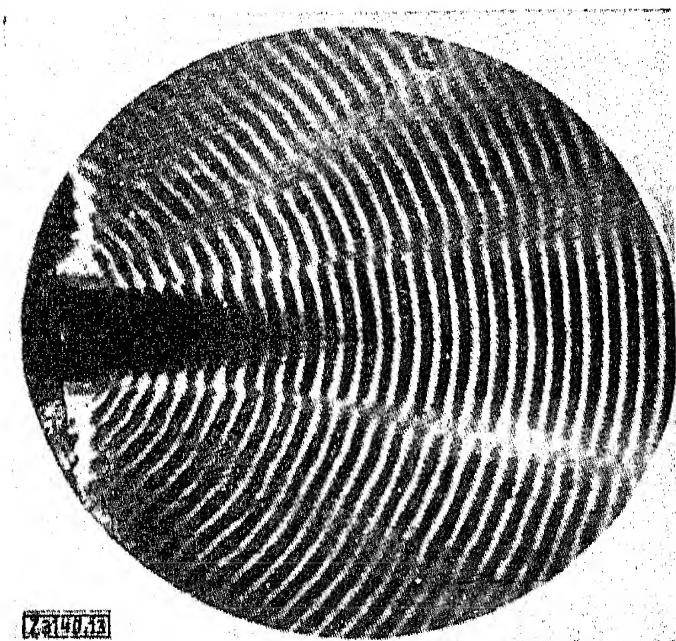
(a)



(b)



(c)



(d)

FIG. 82. Sound waves made visible by the method of secondary interferences : (a) Stationary sound waves in xylol. (b) Two stationary sound waves in xylol crossing one another at right angles. (c) Diffraction of a travelling sound wave at a diaphragm. (d) Sound waves proceeding from the end face of a vibrating quartz (Hiedemann and Asbach).

optical magnification in photographs 82 (a)–(c) is about 14-fold. The working out of a very exact method of measuring the wavelength of sound according to this system is to be placed to the credit of Hiedemann and his co-workers. For this purpose, the trough with the sound wave may be given a measurable displacement by means of a micrometer screw, and the number of bright bands passing a fiducial line in the field of view may be counted. In this way we are always observing under like optical conditions, independently of any need for exact parallelism of the light. The method gives us a relative accuracy of 0.001 per cent. in the measurement of sound wave-length, and the absolute velocity of the sound may be determined to 0.01 per cent. Hiedemann and Seifen (215) have used this method for measuring the frequencies of the overtones of a piezoquartz by the distance apart of the lines of a sound-wave grating, and also the flattening of the resonance curve due to damping of the quartz by the liquid, which may be observed from the change in the bands produced by distuning the transmitter.

There is one point more to be noted concerning the interpretation of the phenomena. If we focus the objective  $O_2$  on the surface of the trough on the sound wave, in this way forming an image of the sound wave, so to say, on the screen  $S$ , the arrangement is identical with the striation method first described in section (a) of this chapter (see also figs. 55 and 59), only with the difference that we are now sending exactly parallel light through the sound waves, and not masking off the slit image of the zero order. We have already drawn attention to this point on p. 67 in discussing the experiments of Debye, Sack, and Coulon, who were the first to give a true interpretation of the experiments of Hiedemann and his co-workers on making sound-wave gratings directly visible, by showing that we are dealing with an optical image of the sound waves produced by secondary interferences due to the superposition of diffraction spectra. A deeper and more detailed insight into this state of affairs was given by the experiments of Bär (cf. p. 68). It is obvious that the convergence of the light produced by the bending of the light rays in the sound field must also play a certain part. The images of the ultrasonic grating produced by the Bachem-Hiedemann-Asbach method give the brightest bands when we succeed in focussing the objective  $O_2$  (fig. 81), exactly on a plane

in which the light is most convergent. This is only possible in cases where the lines of convergence lie either on the exit lane of the light from the sound waves, or even further outside, since the lines of convergence in the middle of the sound field cannot be observed directly by an optical system (cf. p. 83). With stationary waves we have the further point, that the position of the lines of convergence is continually displaced in the direction of the light, since the compressions and expansions in the liquid arise and disappear periodically in the case of a stationary wave. If in the equation given on p. 81 for the distance  $y_0$  of the first convergence line from the incidence lane of the light into the sound wave, we take account of the change with time of the index of refraction, assuming it to follow a sine law, we may write for  $y_0$  the equation

$$= \text{const.} \frac{1}{\sqrt{\Delta n \sin 2\pi Nt}}, \text{ if we neglect the change of position}$$

of  $\Delta n$  in the direction of the sound wave. From this it appears that at time  $t = 0$ , for example,  $y = \infty$ , and only acquires its smallest possible value  $y_0$  after a quarter period of the sound vibration, thereafter again becoming infinite. But we are able to show, as is pointed out by Bachem (11), that the convergence bands are present for the longest time just at the point  $y_0$  and near to it. Bachem calculated, in good agreement with experiment, that the eye during a quarter-period has the impression of a band of a maximum width of  $\Lambda/15$ , while during the remaining time of half-period, in which the bands come from infinity and disappear again, they will appear very faint. When a travelling wave is illuminated stroboscopically, the width of the bands is determined by the duration of illumination. Using a Kerr cell, a very short illumination may be attained by putting the high-frequency alternating voltage on to a triode with such a negative grid voltage that only the peaks of the alternating voltage reach to the bent part of the characteristic. We are then able to take from the anode circuit a voltage which is zero for the greater part of the period, with a very steep peak only for a short fraction of the period. If the Kerr cell stroboscope is used as usual with a direct voltage, we get in the case of a travelling wave bands spaced  $\Lambda$  apart; if the direct voltage is omitted, we get double illumination in each period, and a band spacing of

$\Lambda/2$ . The rendering visible of a travelling sound wave has recently been treated theoretically by Pisharoty (366), applying the Raman-Nath theory.

Nomoto (334) has recently described a method of making ultrasonics visible, differing from the arrangement of Bär, Hiedemann, and Asbach, inasmuch as the objective  $O_2$  (see fig. 81) is omitted, and the truly parallel light passing through the sound wave generates on the screen  $S$ , without the use of any further optical system, a set of bright and dark bands, the spacing of which is the same whatever the distance  $D$  between the screen and the trough. A special point of this method, which likewise depends on a sort of secondary interference of the diffraction spectra generated by the sound wave, is that the visibility of the bands changes with the distance. There are places where the bands are specially well formed, and between them again regions where they disappear almost completely. With a sound frequency of 1865 kHz, a path through the sound waves of 1.2 cm and a sound wave-length of 0.78 mm, the following table was obtained for the distance  $D$ , at which the bands were clearly visible or invisible as the case may be.

TABLE V

*The Alternate Appearance and Disappearance of a Sound Wave Image with Increase of Distance between Wave and Screen*

Distance $D$	Optical Result	$D_i$	$\Delta D$
cm		cm	
7	visible, not very clear		
$\approx 28$	very clear		
53–60	invisible	56.5	56.0
$\approx 84.5$	very clear		
109–116	invisible	112.5	
$\approx 140.5$	very clear		56.5
169	invisible	169	
$\approx 197$	clear		56.0
225	unclear, but visible	225	

$D_i$  gives the most sharply defined position at which the bands disappeared. We see that the distance apart of these positions is fairly constant within the limit of measurements.  $\Delta D$  is

independent of the sound intensity ; the goodness of the band picture becomes, however, worse as we go farther away, when the depth of the sound wave, that is, the path of the light through the sound field, is increased.  $\Delta D$ , on the other hand, becomes greater, the less the sound frequency, and the first position of best visibility of the bands shifts away from the emergence plane of the light from the sound wave as the frequency gets smaller. Nomoto, working with 684 kHz, was just able to recognize the bands at  $D = 50$  cm, and found them clearly visible at  $D = 210 \pm 10$  cm. At higher sound frequencies ( $N = 1855$  kHz) the bands were already well formed quite close to the wall of the trough. This again is in agreement with Bär's observations (p. 83), according to which an amplitude grating for light passing through a sound wave is only formed when the sound wave-length is short enough ; that is to say, when the light rays are sufficiently bent. Nomoto starts from the assumptions based on Raman-Nath's considerations, that in the emergence plane of the light we have essentially a phase grating ; he gives a theory for the periodical appearance and disappearance of the bands outside the sound wave, well representing the experimental results. The distance  $\Delta D$  is, he finds, given by the relation

$$\Delta D = \frac{\Lambda^2}{2\lambda}, \text{ that is to say, } \Delta D \text{ is independent of the sound intensity}$$

and length of the path of light through the sound field, but proportional to the square of the sound wave-length and inversely proportional to the light wave-length. The experiments on which Table V is based were made with the light wave-length  $\lambda = 5460 \cdot 7$  Å and a sound wave-length  $\Lambda = 0 \cdot 778$  mm ; this gives for  $\Delta D$  a theoretical value of 55.7 cm, whereas the mean value of the measurements is 56.25 cm. It is not uninteresting that Winkelmann (472 *a*) already observed similar effects in the diffraction of light by an ordinary ruled grating, and discussed it theoretically, a fact first pointed out by Hiedemann. Experimental contributions to the case of a sound-wave grating in this direction were also made by Parthasarathy (352 *a, b*).

Both Hiedemann and his co-workers, and also Nomoto, made use of strictly parallel light for rendering the ultrasonics visible, but Bergmann and Goehlich (51, 52) have shown that divergent light may be used in a very simple way, without any optical system, to give an excellent visibility of stationary ultrasonics.

Fig. 83 gives an elevation and plan of the experimental arrangement. The source of light is a small 4-watt lamp with a straight filament about 12 mm long; in order to cut out light from the side, it is put in a housing, on the front side of which is an iris diaphragm. The lamp is at a distance  $a$ , amounting to some centimetres, in front of the trough  $T$ , in which the ultrasonic wave is generated by means of a quartz. The filament of the lamp is parallel to the sound wave front. The screen  $S$  is placed on the other side of the trough at a distance  $b$ .

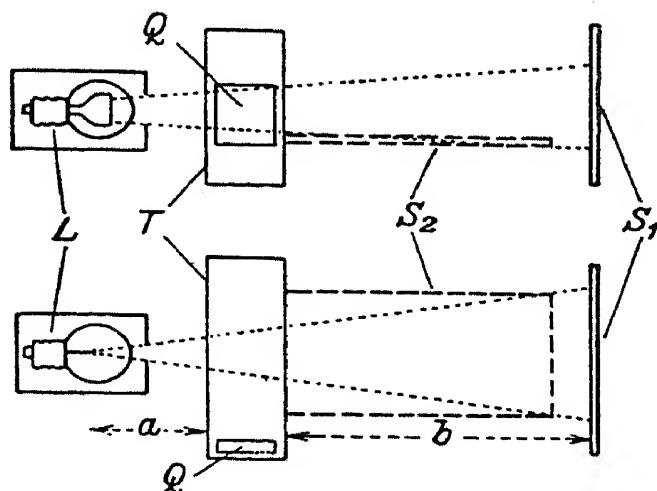


FIG. 83. Experimental arrangement for rendering ultrasonics visible by divergent light (Bergmann and Goehlich).

wave is now produced in the trough, we get bright and dark bands on the screen, as shown twice magnified in fig. 84. The frequency of the sound wave, which was generated in xylol,

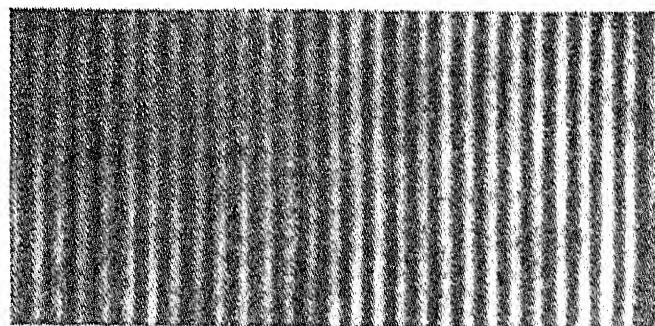
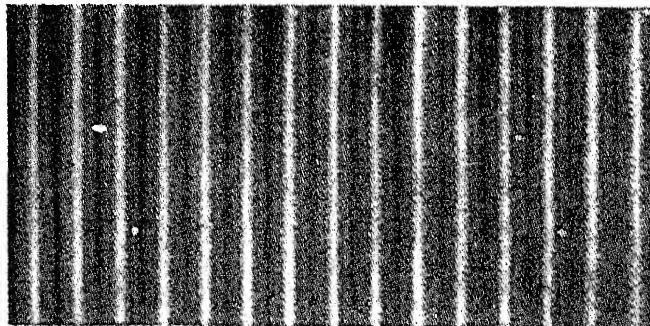


FIG. 84. Central projection of stationary sound waves in xylol at two different frequencies: left, 1650 kHz; right, 3060 kHz (Bergmann and Goehlich)

was 1650 kHz (left picture) and 3060 kHz (right picture), the distances  $a$  and  $b$  being 14 and 47 cm respectively. As we see, the bright bands are comparatively clearly defined. The light intensity is so great that the bands are clearly seen at a distance of 3 metres on a screen, using the small glow-lamp.\*

With higher sound frequencies, these bright bands are already present where the light emerges from the trough. This may

\* The great simplicity of the arrangement, and its freedom from all optical apparatus, renders this method suitable both for demonstration purposes and also for determination of the sound velocity in a practical class.

e shown by putting a screen or a photographic plate in the osition  $S_2$  (fig. 83), so that the beam of light after passing through the trough with the sound waves glances over it. This gives us the fig. 76 already reproduced.

These experiments are only possible with stationary waves, the whole phenomenon being blurred when travelling waves are used. On the other hand, in this case we get another phenomenon, which is particularly strong with high frequencies of the order of 10,000 kHz and above, corresponding in xylol to a sound-wave length of at most 0.1 mm. Using, namely, this divergent illumination with travelling sound waves, only one single light ray is formed by the sound wave, accompanied left and right by two narrow light rays, separated from the middle ray by clear dark spaces. Fig. 85 shows the picture visible on screen  $S_1$  (fig. 83). Fig. 86 (a), on the other hand, shows the phenomenon when the photographic plate was put in the position  $S_2$  so that the light travelling through the trough glanced over the plate. We recognize how extraordinarily sharply the light ray  $p$  passing through the sound wave is formed. Its direction is conditioned by the direction of the sound wave, it being always exactly parallel to the wave front. If the piezoquartz source is turned slightly the light ray  $p$  turns to the side through the same angle (fig. 86 (b)), corresponding to the turn in the sound-wave front with unchanged positions of trough and lamp. We see to the right of this photograph a diagram showing the arrangement of lamp, trough, and quartz. If several sound waves are travelling in the liquid in different directions, and so with differently orientated wave fronts, we get several light rays. Thus, fig. 86 (c) shows, besides the primary ray  $p$  corresponding to the primary wave produced by the quartz  $Q$ , two further light rays  $r$  and  $r'$ , which are to be ascribed to the sound wave reflected at the oblique reflecting plate  $R$ , and to the wave reflected a second time at the quartz. Fig. 86 (d),

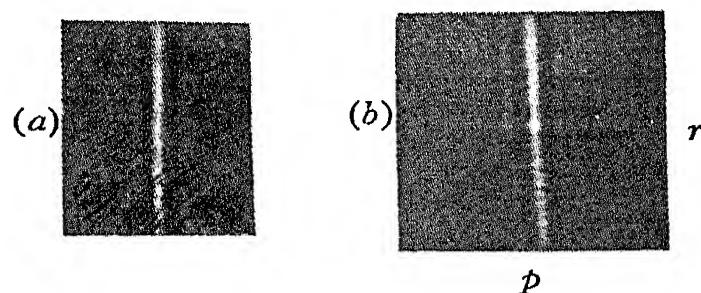
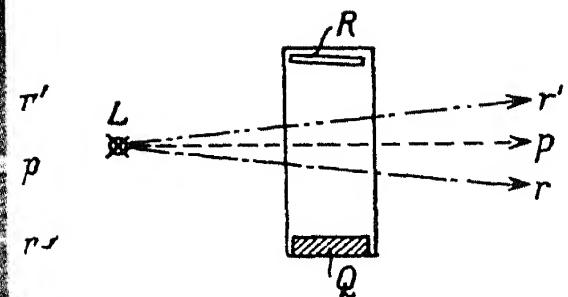
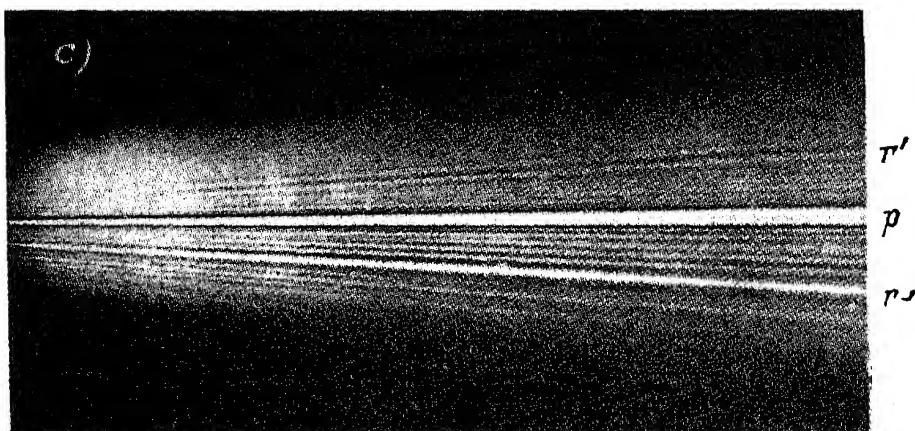
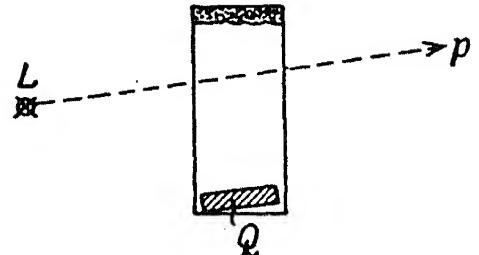
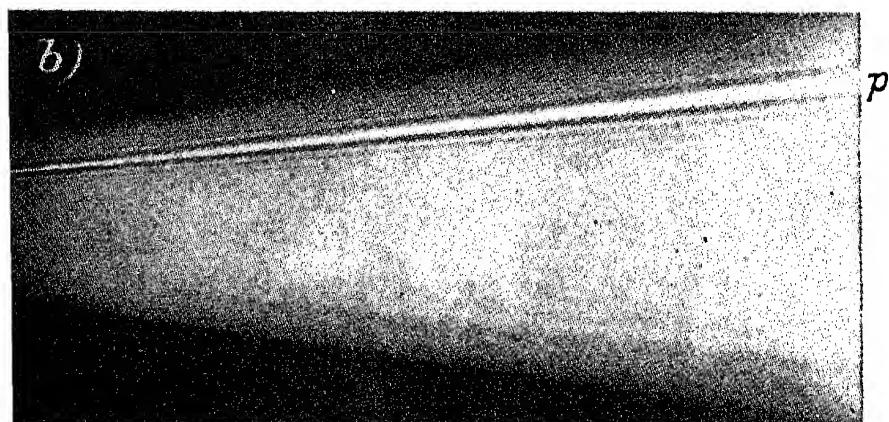
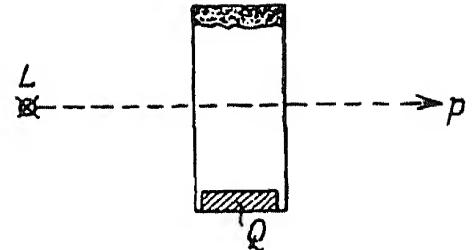
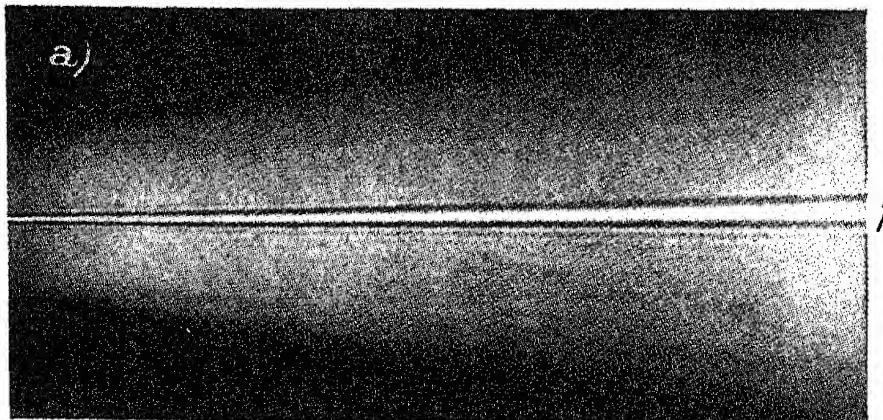
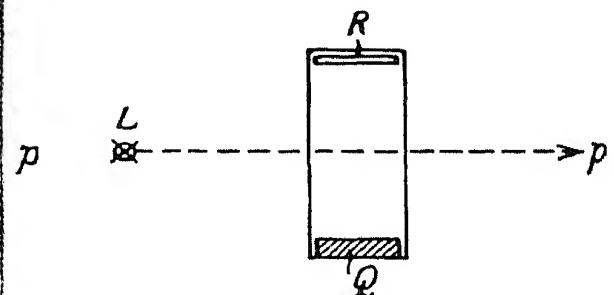
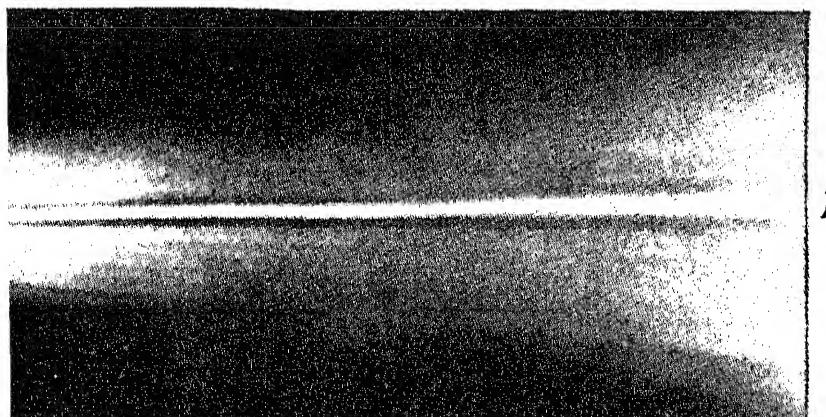
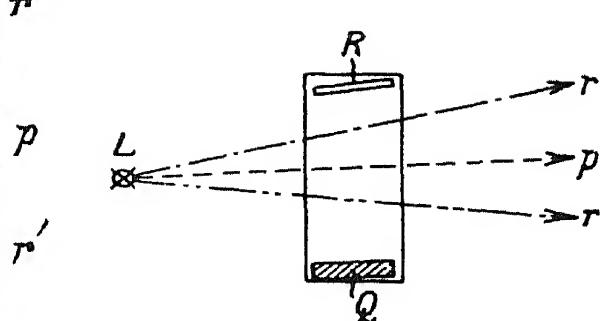
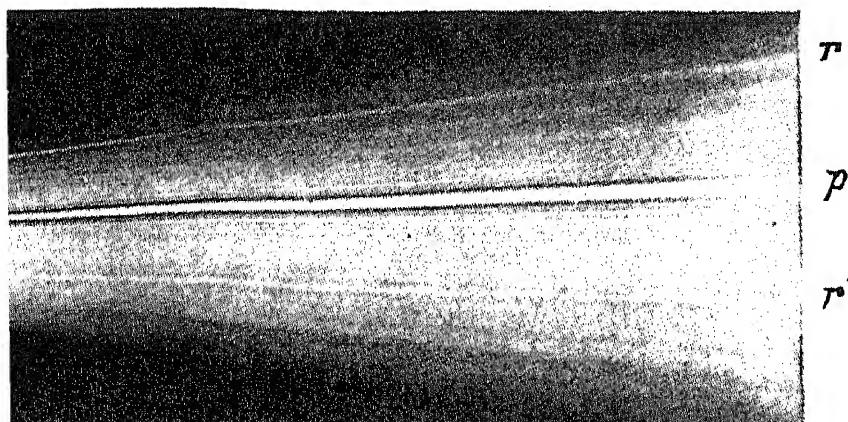


FIG. 85. Appearance of a bright band of light through a travelling sound wave (a) and through two sound waves crossing at right angles (b) of which  $p$  is derived from the primary and  $r$  from the reflected sound wave (Bergmann and Goehlich).

hardly the light ray  $p$  passing through the sound wave is formed. Its direction is conditioned by the direction of the sound wave, it being always exactly parallel to the wave front. If the piezoquartz source is turned slightly the light ray  $p$  turns to the side through the same angle (fig. 86 (b)), corresponding to the turn in the sound-wave front with unchanged positions of trough and lamp. We see to the right of this photograph a diagram showing the arrangement of lamp, trough, and quartz. If several sound waves are travelling in the liquid in different directions, and so with differently orientated wave fronts, we get several light rays. Thus, fig. 86 (c) shows, besides the primary ray  $p$  corresponding to the primary wave produced by the quartz  $Q$ , two further light rays  $r$  and  $r'$ , which are to be ascribed to the sound wave reflected at the oblique reflecting plate  $R$ , and to the wave reflected a second time at the quartz. Fig. 86 (d),



finally, shows the case when the reflecting plate is turned to the other side, whereby the light ray  $r$  is likewise deflected to the other side of the primary ray  $p$ ; the ray  $r'$ , to be ascribed to the wave reflected a second time at the quartz, is also faintly indicated. If the quartz  $Q$  and reflector plate  $R$  are set exactly parallel, so that stationary waves are formed, the light rays belonging to the outgoing and reflected wave become one, as we see in fig. 86 (e). In this case also the fine structure produced by the stationary sound wave appears in the whole beam of light,



6. Track of the light when divergent light is sent through a travelling ultrasonic at different positions of vibrating quartz and reflector (Bergmann and Goehlich).

already shown in fig. 76, for a considerably lower sound frequency. This experimental arrangement thus gives us the possibility of an optical method of adjusting the quartz source and also the reflecting plate very exactly, which is of great use in many cases when measurements of precision are to be made. The sound waves travelling in other directions may also be made visible in the same manner; we use in place of a line source of light a point source. Fig. 85 (b) shows the case of two sound waves crossing one another at right angles.

The following explanation of the appearance of these single light rays of light when divergent light is sent through a sound wave may be put forward. As fig. 86 (a) to (e) shows, the intensity of the light ray going through the sound wave parallel to the wave front is greater than the intensity of the light going through an oblique direction. The single light ray is also more brilliant than the light going through the trough when the sound

wave is not present. It thus appears as if light from neighbouring parts is refracted or diffracted by the sound wave into the central ray. This would be possible according to fig. 75 at a compression point of the sound waves, as suggested by Lucas and Biquard, this being the point at which the light enters exactly at right angles; that is to say, the emergent light ray must be parallel to the wave front. This would also explain the particularly dark parts at the two sides of the ray, and also the fact that the ray is sharper and narrower the higher the frequency of the sound. The fact that the phenomenon appears with travelling waves as well as with stationary waves may be explained by the fact that a symmetrical concentration of rays from the whole divergent beam of light to form one ray is only possible in the position where the light travels through the sound-wave grating exactly parallel to the wave front. We shall therefore always have on the average a greater intensity of light let through the sound wave at this point than in neighbouring parts, where the oblique incidence and the motion of the sound-wave grating causes the light traversing it to be blurred to an average even brightness.

**4. The Diffraction of Light at Several Sound Waves Crossing one Another.** We have so far discussed the diffraction of light only at a single sound wave, and one in general plane; this problem is therefore the diffraction of light by a one-dimensional grating. If now two sound waves cross one another in a liquid, for example at right angles, we get a cross grating (for example, fig. 82 (b)) and hence with light a cross-grating spectrum. For this purpose it is naturally necessary to replace the slit by a circular aperture. A spectrum of this sort is shown in fig. 87 (a). The source of sound was a quartz in xylol, and the sound wave proceeding from its surface was so reflected by a reflector inclined at  $45^\circ$  that it crossed the incident wave at right angles. If two quartzes are used as sources, it is obviously possible to produce crossed grating spectra with grating constants different in the two directions. There is no need to reproduce such spectra. They were published almost simultaneously by Bär and Meyer (26), Hiedemann and Asbach (206), and Schaefer and Bergmann (409 to 412). Finally, fig. 87 (b) shows a cross-grating spectrum produced by three waves of the same frequency crossing one another at  $120^\circ$ .

It was now natural to go one step further and form a three-dimensional space grating of elastic waves by three ultrasonics at right angles; we should then expect with visible light space-grating interference effects similar to those produced by the

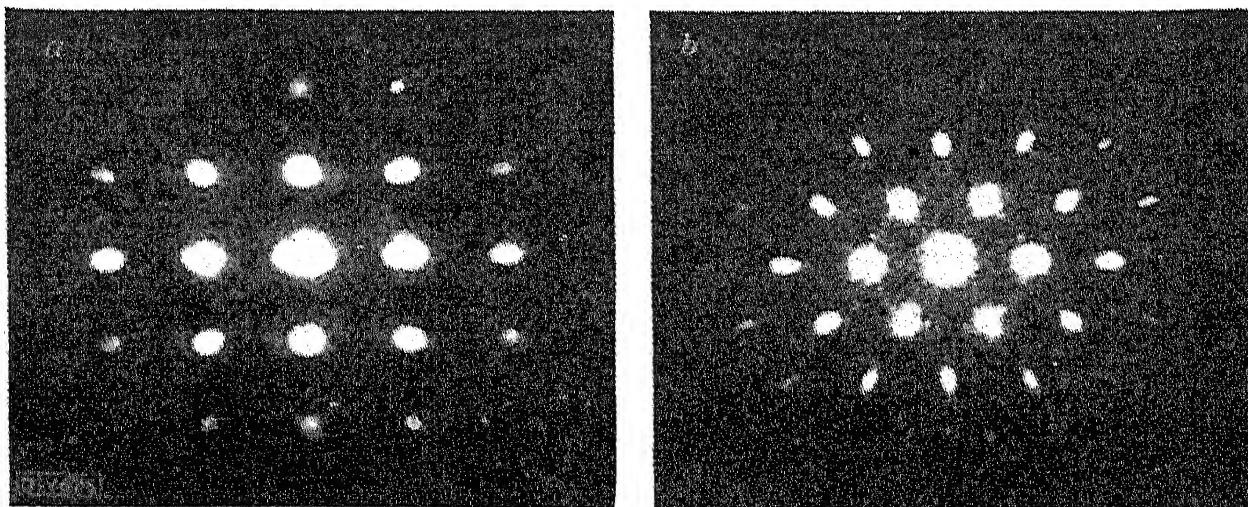


FIG. 87. (a) Diffraction image formed by two ultrasonic waves crossing at right angles. (b) Diffraction image formed by three ultrasonic waves meeting at an angle of 120 (Schaefer and Bergmann).

Diffraction of X-rays by crystal lattices. Systematic experiments in this direction were first made by Schaefer and Bergmann (409 to 411). Hiedemann and Asbach (206) also published independently and almost simultaneously some indications of

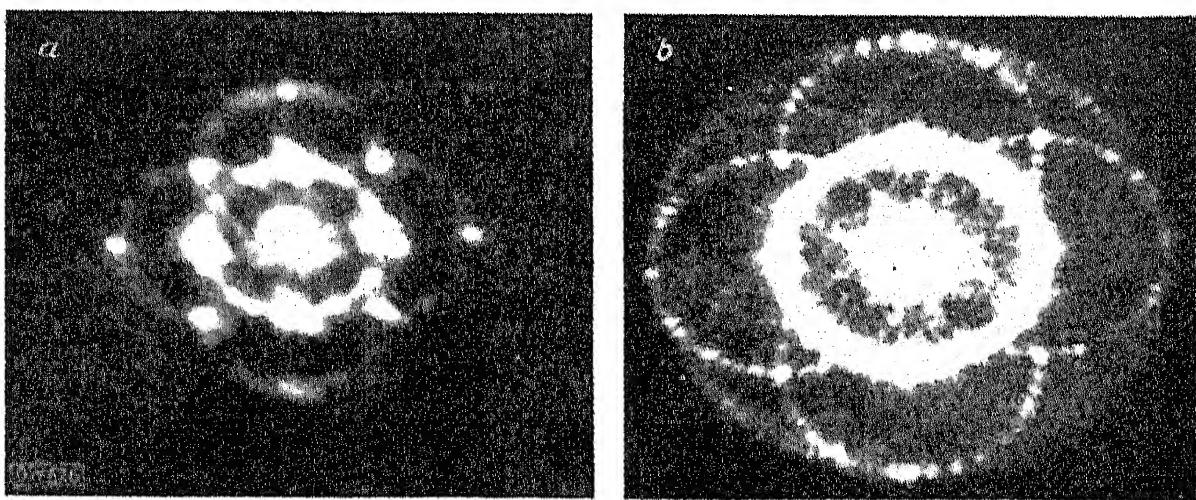


FIG. 88. Diffraction images of a space grating produced in a liquid by several crossing ultrasonic waves (Schaefer and Bergmann).

space-grating interference in the diffraction of light by sound waves reflected several times. Fig. 88 (a) shows one of the first interference figures produced by the diffraction of light by three sound waves of equal frequency crossing one another at right

angles ; it is very similar to a bad Laue photograph taken with a regular crystal. The three sound waves were produced in this case by three quartz plates at right angles to one another, and having the same natural frequency, in a trough filled with xylol. The beam of light then went through one of the quartzes. It was later found possible to produce this space-grating interference by suitable multiple reflection of a single sound wave. Fig. 88(b) shows a particularly good photograph. It was produced by exciting a cubical glass trough filled with a liquid, and having edges about three centimetres long, to high-frequency oscillations by means of a piezoquartz pressed against the bottom of the trough. In this case the vertical glass walls of the trough are also set in vibration, and elastic waves are formed in the liquid in all three directions at right angles to the surface of the cube. The theory of the diffraction of light by such ultrasonic space gratings is given by Fues and Ludloff (159). We will go into it more fully in Chapter IV. Here there is no need to say more than that the theory for the diffraction of light by an ultrasonic space grating in a liquid gives as diffraction image of the first order a simple circle. This is seen in fig. 88 (b) as a particularly brilliant circle. Its radius  $r$  is connected with the sound velocity  $v$  in the liquid, the sound frequency  $N$ , the light wave-length  $\lambda$ , and the distance  $A$  of the plane of formation of the image by the

relation  $v = \frac{A\lambda N}{r}$ , which passes over into the relation given on

p. 65 for the diffraction of light by a plane sound wave, when we put for  $r$  the distance of the first diffraction image from the central image of the slit. The remaining circles in fig. 88 (b) are already diffractions of a higher order. We are able to see very beautifully the process of multiple diffraction, since every point of the bright inner circle produces by space-grating diffraction a new circle round itself. The envelope of all these circles is a circle with radius  $2r$ , which may be regarded as the diffraction picture of the second order with respect to the inner point.

Fig. 89, finally, gives the case in which the sound wave running through the liquid horizontally is particularly intense. The diffraction points of the first to third order come out very strongly. But we then get round each diffraction image, on account of the multiple diffraction, a further circle which is of

exactly the same size as the circle round the middle point of the picture.

The optical methods discussed on pages 58-102, for the detection and measurement of ultrasonics, may be applied not only to the propagation of sound waves in liquids and gases, but may also be used to render visible directly or indirectly sound waves in solid transparent bodies in the same way. In such bodies ultrasonics may be generated by cementing a piezo-

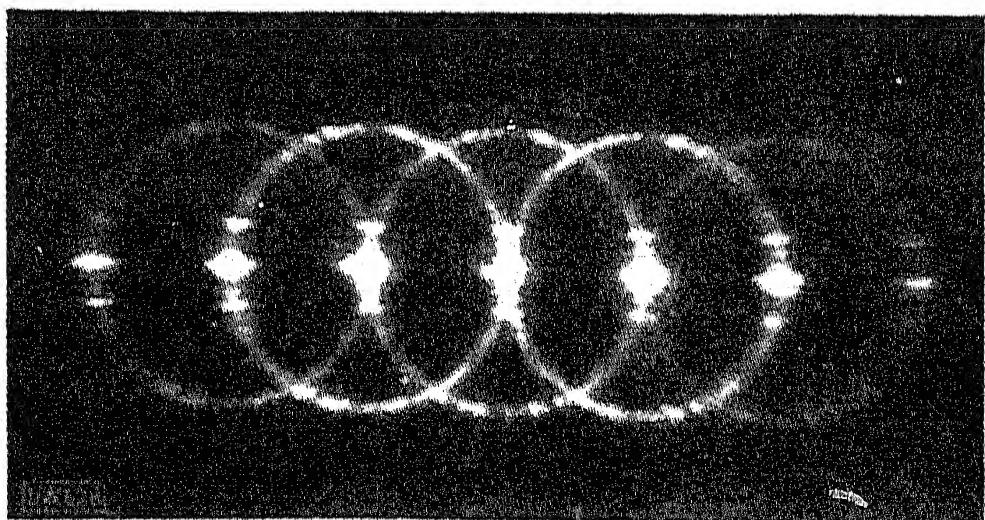


FIG. 89. Multiple diffraction of light at a system of sound waves in a liquid (Schaefer and Bergmann).

quartz to a plane surface of the body, or by pressing it firmly against it with a thin layer of oil interposed. But as compared with liquids and gases, we always get in solids the formation of stationary waves on account of the reflection of the sound at the boundaries, which are at a finite distance. In addition, the vibration of the body in the remaining directions, caused by lateral contraction, leads to a further formation of stationary waves, so that a solid body set in high-frequency vibration has usually a very complicated sound-wave grating. We shall return to this point in further detail on p. 164.

## CHAPTER III

### THE MEASUREMENT OF VELOCITY AND ABSORPTION OF SOUND IN LIQUIDS AND GASES

IN the second part of this book we shall deal with the manifold applications of ultrasonics in physics, chemistry, and technology. One of the chief fields of application is in the measurement of the velocity of sound.

(a) The Velocity of Sound in Liquids, and its Measurement. We already stressed the fact in the Introduction that measurements of sound velocity are particularly simple in the ultrasonic range, since, firstly, the influence of the walls of the experimental vessel, so disturbing in the case of longer waves, is practically negligible with these short waves, so that elaborate corrections are unnecessary; and secondly, the use of ultrasonics makes it possible to carry out velocity measurements on very small amounts of substance. When optical methods are used for wave-length measurements, a few cubic centimetres are frequently sufficient, whereby very accurate measurements of velocity may be performed on liquids difficult to obtain, or very volatile. Examples are afforded by recent measurements of the velocity of sound in liquid oxygen and in heavy water (18, 20, 289).

Assuming that the vibration takes place adiabatically, that is to say, that the pressure changes are so rapid as to prevent in- and out-flow of heat from and to the surroundings, the velocity of ultrasonics  $v$  in a liquid of density  $\rho$  is given by the relation

$$v = \sqrt{\frac{\kappa}{\rho \beta_{is}}} = \sqrt{\frac{1}{\rho \beta_{ad}}},$$

where  $\beta_{is}$  is the compressibility at constant temperature,  $\beta_{ad}$ . the adiabatic compressibility, and  $\kappa = \frac{c_p}{c_v}$  the ratio of the specific heats. The compressibility  $\beta$  is defined as the decrease in

volume  $dv$  caused by increase of pressure  $dp$ , for unit volume. If the volume is  $V$ , we get

$$\beta = \frac{1}{V} \frac{dv}{dp}.$$

The compressibility  $\beta$  is usually given in  $\text{atm}^{-1}$ . In order to get the velocity of sound in  $\text{cm/s}$ , these values have to be divided by 1,013,300, since  $1 \text{ atm} = 980.66 \times 1033 = 1,013,300 \text{ dyn/cm}^2$ . The change in the velocity of sound with temperature is mainly determined by the dependence of the compressibility on temperature. While in the case of water the compressibility decreases both with increase of temperature and increase of pressure, whereby the velocity of sound in it increases, all other liquids on the contrary show a considerable increase in compressibility with temperature, resulting in a decreased velocity of sound. A dispersion of the velocity of sound in liquids has never been detected with certainty. Special experiments in this direction, leading to a negative result, were carried out by Parthasarathy (351) and Spakovskij (439). Quite recently Hiedemann, Seifen, and Schreuer (216) believe that they have found, in measurements undertaken with the greatest accuracy on toluol and xylol, an increase in the velocity of sound of about 1  $\text{m/s}$  with an increase of frequency from 4800  $\text{kHz}$  to 8400  $\text{kHz}$ ; water showed no such effect in this range. But the data are still too scanty to allow a decisive conclusion to be drawn.

The chief importance of sound velocity measurements in liquids lies in their rendering possible a determination of the adiabatic compressibility. Given this, and the isothermal compressibility derived from static measurements, we are able to calculate the ratio of the specific heats of a liquid. This then gives us the value of the specific heat at constant volume  $c_v$ , which is otherwise only calculable by means of very complicated thermodynamic relations (233, 425). Conversely, we are naturally also able to determine the isothermal compressibility  $\beta_{is}$  by means of the ultrasonic value of  $\beta_{ad}$ , when either  $\kappa = \frac{c_p}{c_v}$  is known for the liquid in question, or when the thermal coefficient of expansion  $\alpha$  is given. We have the well-known formula \*

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\* See Planck, *Thermodynamics*, p. 126 (London, 1927).

$$c_p - c_v = \frac{T \alpha^2}{\beta_{is} \rho} \quad (T = \text{absolute temperature}),$$

and since

$$v^2 = \frac{\kappa}{\beta_{is} \rho} = \frac{c_p}{c_v \beta_{is} \rho}$$

we get

$$c_p = \frac{T a^2 v^2}{v^2 \beta_{is} \rho - 1}.$$

From this it follows that

$$\beta_{is} = \frac{c_p + T \alpha^2 v^2}{v^2 \rho c_p} = \beta_{ad} + \frac{T \alpha^2}{\rho c_p}.$$

Sound velocity measurements in solutions give us a connection between compressibility and concentration, which allows of a number of interesting questions in the modern theory of

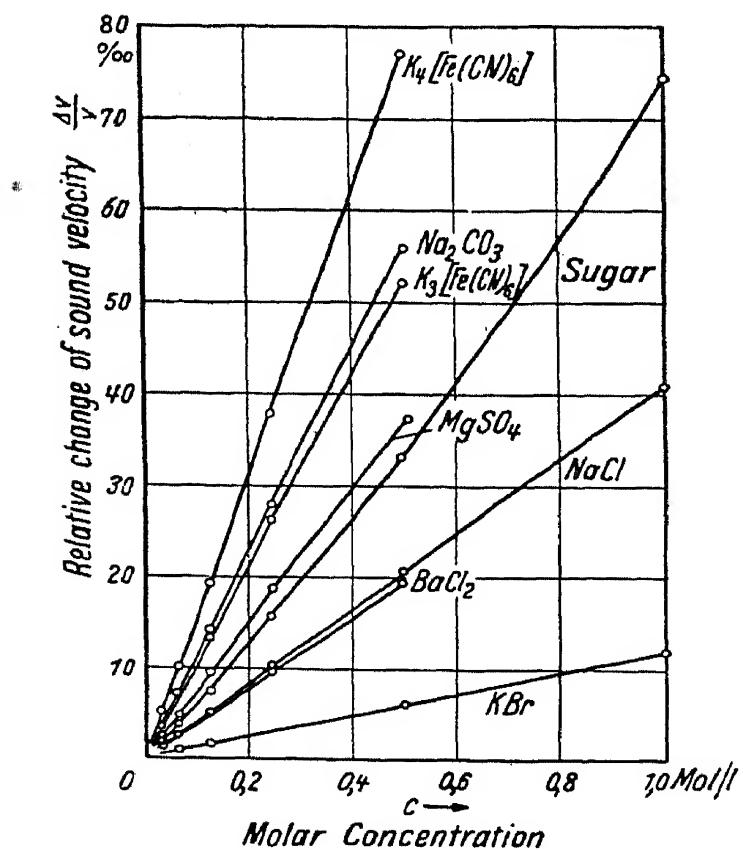


FIG. 90 Dependence of velocity of sound on concentration (Bachem).

electrolytes being tested. To mention only one or two points, we have, for example, that, according to Gucker (178, 179), the apparent molar compressibility  $K$  of electrolytes is linearly dependent on the square root of the molar concentration  $c$  according to the equation

$$K = a + b\sqrt{c}.$$

Here  $\alpha = (K)_0$  the apparent molar compressibility at infinite dilution, which changes from electrolyte to electrolyte, and  $b = \left( \frac{\partial K}{\partial \sqrt{c}} \right)_0$  the slope of the straight line representing the dependence of  $K$  on the square root of  $c$ .

This relation was tested by Falkenhagen and Bachem (143) in the region of very small concentrations by the use of sound velocity measurements on electrolytes; they found that it was confirmed. On the other hand, non-electrolytes, for example

sugar, showed an almost linear relation between the apparent molar compressibility and the molar concentration. Fig. 90 is plotted from measurements made by Bachem, using the method of secondary interferences described on p. 89. It gives the dependence of the velocity of sound on the concentration for a number of solutions. We have as abscissæ the molar concentration in mol/l, as ordinates the relative change of the velocity of sound  $dv/v$  in parts per thousand. We recognize the strictly linear form of the curves for all electrolytes, while the measurements on sugar give a non-linear curve.

The compressibility  $\beta$  follows for electrolytes the law

$$\beta = \beta_1 + Ac + Bc^{3/2},$$

here  $\beta_1$  means the compressibility of the pure solvent,  $A$  and  $B$  being constants which may partly be calculated for a certain electrolyte, and partly determined by experiment. We have

$$A = \frac{1}{1000}(K_0 - \beta_1 \Phi_0) \quad \text{and} \quad B = \frac{1}{1000} \left[ \left( \frac{\partial K}{\partial \sqrt{c}} \right)_0 + \beta_1 \left( \frac{\partial \Phi}{\partial \sqrt{c}} \right)_0 \right],$$

where  $\Phi_0$  denotes the apparent molecular volume at infinite dilution, and  $\left( \frac{\partial \Phi}{\partial \sqrt{c}} \right)_0$  the slope of a straight line representing

the linear dependence, discovered by Masson (323), of the apparent molecular volume on the square root of the molar concentration  $c$  (161). For example, we have, according to Geffken,\* for a solution of KBr in water at 25°,

$$\Phi_0 = 33.54 \text{ cm}^3, \quad \left( \frac{\partial \Phi}{\partial \sqrt{c}} \right)_0 = 2.06,$$

$$K_0 = -37 \times 10^{-10} \quad \text{and} \quad \left( \frac{\partial K}{\partial \sqrt{c}} \right)_0 = 8.2 \times 10^{-10},$$

hence  $A = -52 \times 10^{-13}$ , and  $B = 9.12 \times 10^{-13}$  (all numbers being in C.G.S. units) and so, since for water as solvent  $\beta_1 = 484 \times 10^{-13}$ , we have

$$\beta_{\text{KBr}} = 483 \times 10^{-13} - 52 \times 10^{-13}c + 9.12 \times 10^{-13}c^{3/2}.$$

This gives us for a solution of concentration 1 mol/l a reduction of compressibility of 10 per cent. as compared with the solvent. The measured change in sound velocity amounts to about

\* *Z. Phys. Chem. (A)*, 155, 1 (1931).

12°/oo, since for  $\Delta v$  it is necessary to take into account, besides the change in compressibility, also that in density, which is greater than in the case of the pure solvent. For small changes, it follows from the equation for the velocity of sound  $v^2 = \frac{1}{\beta_{ad}\rho}$  that

$$-\frac{\Delta\beta_{ad}}{\beta_{ad}} = 2\frac{\Delta v}{v} + \frac{\Delta\rho}{\rho},$$

from which the relative change of compressibility may be calculated for the measured velocity of sound and the known change in the density of solutions. Similar measurements of compressibility by the method of sound velocity were also carried out by Szalay (455). He also found for electrolytes a decrease in compressibility with increase of concentration. Table VI shows the relative changes in velocity of sound, density, and compressibility as compared with the solvent water, for a number of *N/10* electrolytes.

TABLE VI

*Relative Change of the Velocity of Sound, Density, and Compressibility for some Solutions of Electrolytes*

<i>N/10</i>	°/oo		
	$\Delta v/v$	$\Delta\rho/\rho$	$\Delta\beta/\beta$
KBr . .	1.28	8.5	11.1
KCl . .	3.38	4.8	11.6
NaCl . .	3.9	4.2	12.0
LiCl . .	3.7	2.6	10.0
MgSO <sub>4</sub> . .	7.4	13.1	27.9
ZnSO <sub>4</sub> . .	6.3	16.3	28.9
CdSO <sub>4</sub> . .	2.9	20.4	26.2
Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> . .	17.4	30.0	64.8

Ions with the same charge give about the same effect, so that we may conclude that the effect depends chiefly on the charge and not on the radius of the ion. The change of compressibility is more than linear and less than quadratic in the case of multi-valent ions. The fact that lithium chloride has a somewhat greater departure from linearity is to be explained according to

Szalay by the special position of lithium in the periodic system. The monovalent ions give us a mean value for  $\Delta\beta/\beta$  of  $11.2\%$ . The three bivalent ionic solutions measured give as mean value  $27.6\%$ . The explanation of the decrease of compressibility of electrolytes may be given, according to Debye (124, 455), by the action of the electric field round each ion on the water, that is to say, the electrostatic pressure, which may be of the order of 10,000 atm, and causes an additional contraction of the water. This causes a decrease in the compressibility of the solution in the same way as is caused by increasing external pressure.\* Debye's theory gives as a first approximation for the dependence of the effect on the ionic charge, that it should depend on the 1.5-th power of the charge. This is in agreement with experiments as regards order of magnitude.

These examples may suffice to show how valuable exact sound velocity measurements in liquids are for our knowledge of molecular properties. We will refer later to some connections between sound velocity and chemical constitution.

We will now discuss a number of practically tested methods for measuring sound velocity in liquids. The first exact measurements with ultrasonics were carried out by American investigators, using interferometers (156, 227, 229, 230). We have already discussed the principle of the ultrasonic interferometer originated by G. W. Pierce (361) on p. 56. Fig. 91 shows one of

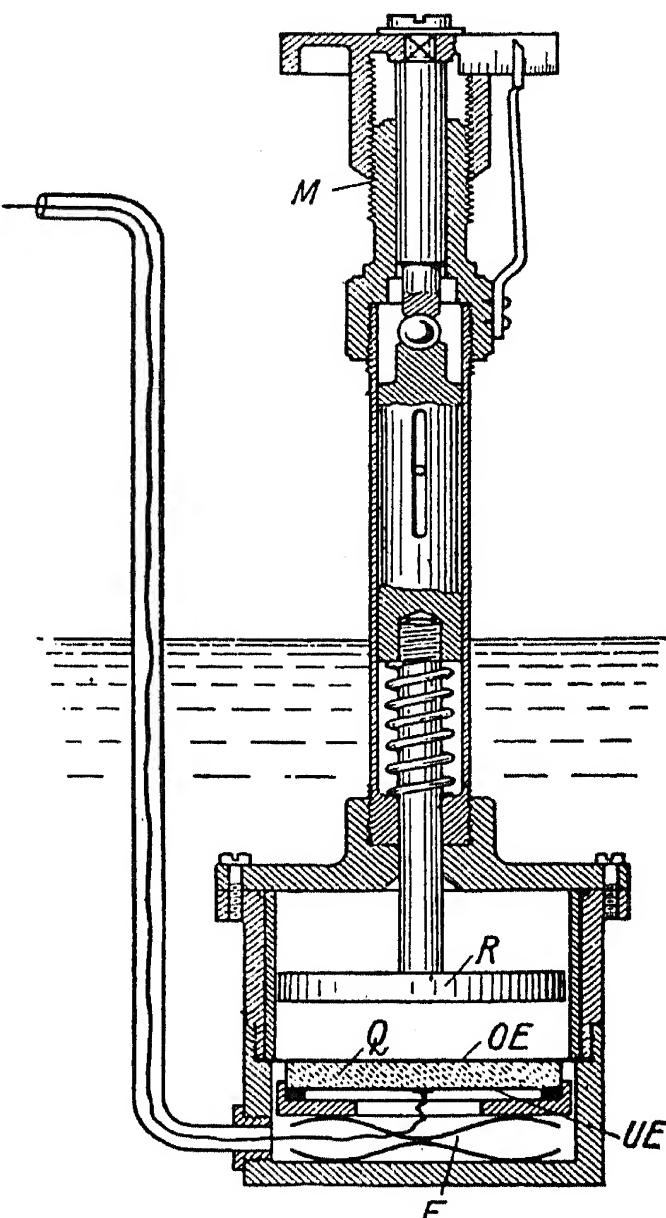


FIG. 91. Acoustical interferometer for liquids.

\* See, for example, *International Critical Tables*, 3, 40 (measurements by Bridgman).

the most commonly used forms of ultrasonic interferometer. The source of sound, a piezoquartz  $Q$ , is situated in the lower part of a vessel which can be taken apart, and is usually cylindrical. The upper electrode  $OE$  is formed by thin bronze foil, which at the same time serves to separate the quartz completely from the upper vessel in which the sound waves are to travel. This prevents the quartz from being wetted by the liquid under investigation, and so being short-circuited electrically. The lower surface of the quartz is metallized. A spring  $F$  acting through an interposed ring of metal presses the quartz against the foil  $OE$ . The reflecting plate  $R$  may be displaced by means of a micrometer screw  $M$ . Suitable mechanical means are employed to prevent the reflecting plate from turning, and to take up backlash. The connection to the upper quartz electrode is formed by the metallic vessel itself, that to the lower goes through an insulating tube which fits water tight into the lower chamber, so that the whole interferometer may be put into a bath of liquid in order to keep the temperature constant. Special care must be taken to see that the quartz is everywhere in close contact with the metal foil. In order to get enough sound energy into the vessel, that is to say, in order that the quartz may vibrate strongly, the pressure of it on the metallic foil must be neither too great nor too small; in the latter case, too, a distortion of the wave front takes place, which leads to disturbances in measuring the stationary wave. Now the most favourable pressure again depends upon the liquid under investigation. It may be adjusted by change in the pressure of the spring  $F$ . This can be changed during the measurement, and without taking the interferometer out of the bath, only with great difficulty.

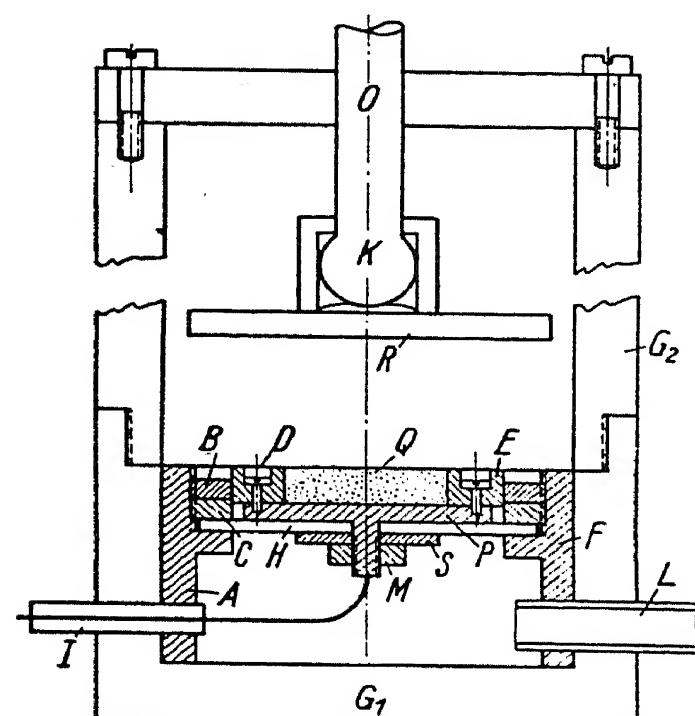


FIG. 92. Acoustical interferometer for liquids (Quirck and Rock).

This difficulty is skilfully avoided in a construction given by Quirck and Rock (371), fig. 92. In the lower part  $G_1$  of the inter-

metallized. A spring  $F$  acting through an interposed ring of metal presses the quartz against the foil  $OE$ . The reflecting plate  $R$  may be displaced by means of a micrometer screw  $M$ . Suitable mechanical means are employed to prevent the reflecting plate from turning, and to take up backlash. The connection to the upper quartz electrode is formed by the metallic vessel itself, that to the lower goes through an insulating tube which fits water tight into the lower chamber, so that the whole interferometer may be put into a bath of liquid in order to keep the temperature constant. Special care must be taken to see that the quartz is everywhere in close contact with the metal foil. In order to get enough sound energy into the vessel, that is to say, in order that the quartz may vibrate strongly, the pressure of it on the metallic foil must be neither too great nor too small; in the latter case, too, a distortion of the wave front takes place, which leads to disturbances in measuring the stationary wave. Now the most favourable pressure again depends upon the liquid under investigation. It may be adjusted by change in the pressure of the spring  $F$ . This can be changed during the measurement, and without taking the interferometer out of the bath, only with great difficulty.

This difficulty is skilfully avoided in a construction given by Quirck and Rock (371), fig. 92. In the lower part  $G_1$  of the inter-

ferometer vessel is fitted a sleeve *A*, provided with a ring-shaped ledge *F*. An ebonite disc *H* is pressed firmly against this by the screwed ring *B* acting through a brass washer *C*. On the upper side of the ebonite plate we have a brass plate *P*, truly plane, which is held on the ebonite disc by a screwed rod soldered to its middle point and carrying the nut *N* and washer *S*. It forms the lower electrode of the piezoquartz. The quartz is held in position by a ring *E* of insulating material. On the upper electrode we have again a thin bronze foil *D* which forms, when the upper interferometer vessel *G*<sub>2</sub> is screwed on, an air- and water-tight diaphragm between *G*<sub>1</sub> and *G*<sub>2</sub>. The connection to the lower quartz electrode is carried air-tight through an insulating tube *I*. The tube *L* allows the air pressure in the lower chamber to be changed in any desired way, say by lifting or lowering a vessel of mercury; in this way the pressure of the quartz against the metal foil *D* may be changed during a measurement, and adjusted to the most favourable value. A further point is a very convenient fixing for the reflecting plate *R* on the screw spindle *O*, consisting of a ball joint *K*. In order that the plate may be set exactly parallel to the surface of the quartz, a point of great importance for precise measurements, it is screwed down at the start until it is in contact with *D*. The ball joint enables the plate to set itself parallel to *D*, where it also remains after it has been raised, assuming that it does not turn during this process, as is the case when it is suitably guided (see, for example, fig. 91, p. 109).

Other designs similar to these interferometers are to be found in the literature (229, 155, 156, 250). Here we will refer to only one more special construction by Swanson (450) which was built for ultrasonic measurements in liquids under very high pressures, up to about 1000 atm. Measurements of this sort, which are only possible with ultrasonics, have hitherto only been carried out in very few cases, and the literature gives us hardly any data concerning the change of sound velocity with pressure. The

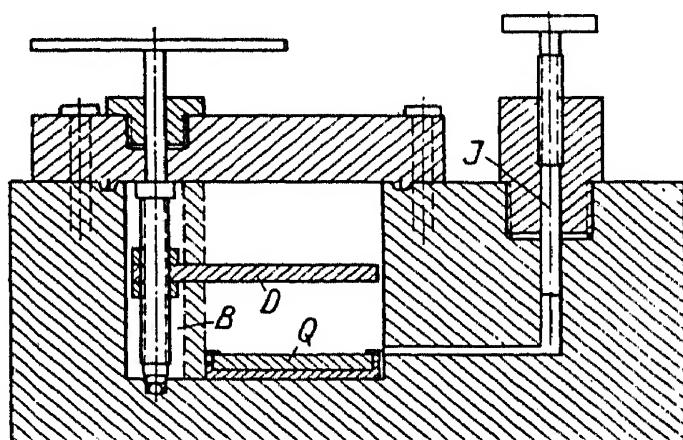


FIG. 93. Acoustical interferometer for sound velocity measurements at high pressures (Swanson).

whole construction, including the quartz, movable reflector, etc., is contained in a steel block  $20 \times 12 \times 11$  cm, as shown in section in fig. 93. *Q* is the piezoquartz plate, *B* the reflector, which may be displaced by the screwed rod *D*, *J* is a piston for producing the high pressures. Swanson recently measured with this apparatus the change in the velocity of sound with pressure over a range of 1 to 300 atm for nine different organic liquids, obtaining the values given in Table VII, from which we may calculate, for example, the specific heat at high pressure (451, 452).

TABLE VII

*The Dependence of Velocity of Sound in Organic Liquids on Pressure*

Liquid	$C_2H_5Br$	$CCL_4$	$CHCl_3$	$C_2H_5OC_2H_5$	$C_5H_{12}$
at 1 $kg/cm^2$	885	912	986	993	1005 m/s
at 300 $kg/cm^2$	1000	1048	1097	1255	1281 m/s
Liquid	$CS_2$	$C_6H_6$	$C_7H_8$	$C_6H_5NH_2$	
at 1 $kg/cm^2$	1136	1290	1313	1640 m/s	
at 300 $kg/cm^2$	1268	1416	1447	1745 m/s	

Within the range of pressure investigated the dependence of sound velocity on pressure is linear. An ultrasonic interferometer for measurements at very low temperatures, for example, in liquid gases, is described by Pitt and Jackson (367). In liquid oxygen ( $-182.9^\circ C.$ ) they found a velocity 912 m/s (see also p. 119) and in liquid hydrogen ( $-252.7^\circ C.$ ) 1127 m/s.

The sound velocity measurements with these interferometers are conducted by measuring the half wave-length in the liquid under test by shifting the reflector plate. As explained on p. 56, the resonance positions may be determined with great certainty by observing the anode current of the oscillator by which the quartz is excited. Measurements may be carried out in this way so rapidly that the interferometer may be used for measuring the concentration of a solution, or as a saccharimeter. Andrews (6) described an arrangement for recording automatically the distances

apart of the resonance positions, that is to say, the half wave-length. As shown in fig. 94 (a), the drum  $T$  of the micrometer screw has round it a thread running over a pulley  $R$  and moving a photographic film  $F$  in a light-tight case  $G$  behind a slit  $S$ , when the micrometer screw is turned. In the anode circuit of the oscillator driving the quartz we have, as measuring instrument, a mirror galvanometer with sufficient damping, the mirror of which is made to form an image of a bright filament on the slit  $S$ . We then get on the film curves such as are given, for example, in fig. 94 (b), for two series of measurements. The distance apart of the peaks of these curves is then measured, giving the half wave-length of the sound with great exactness, after correction for the mechanical ratio. Hubbard (224), who discusses in general the precautions to be taken in interferometer work, gives  $0.05\%$  as the present attainable accuracy in sound velocity measurement, and points out that it is even possible conversely to calibrate micrometer screws very exactly by using an ultrasonic interferometer arrangement.

An ultrasonic interferometer with optical detection of the positions of resonance has been put forward by Wyss (477). If the image of a slit is formed through the sound wave between the quartz and reflector on a screen, we get diffraction of light by the sound wave as described on p. 63. The intensity of the diffraction phenomenon depends on the sound intensity and becomes a maximum in the case of the formation of stationary waves, that is when quartz and reflector are separated by a multiple of  $\Lambda/2$ . If therefore the distance of the reflector is varied, we get a periodic change of the diffraction images, and this interferometer method, according to Wyss, has an accuracy of  $0.2\%$ .

The distances apart of two successive reflector positions of maximum reaction on the oscillator, or maximum formation of

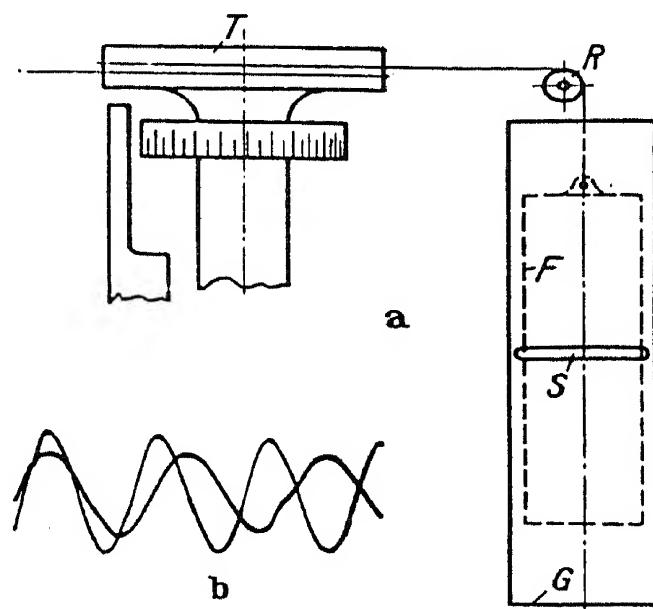


FIG. 94. (a) Arrangement for registering positions of resonance in interferometer measurements. (b) Type of record (Andrews).

optical diffraction effects—we will make use of the term 'intervals'—have the value  $\Lambda/2$  only in the case when the sound wave sent out by the quartz is perfectly plane. This is not the case, for example, when the size of the radiating surface is not great as compared with the wave-length of the sound, or when certain parts of the quartz surface vibrate particularly strongly (p. 21). We then get, when the distances of the reflector from the source are small, false values for the intervals, which may give rise to errors in the measurements. Disturbances of this sort

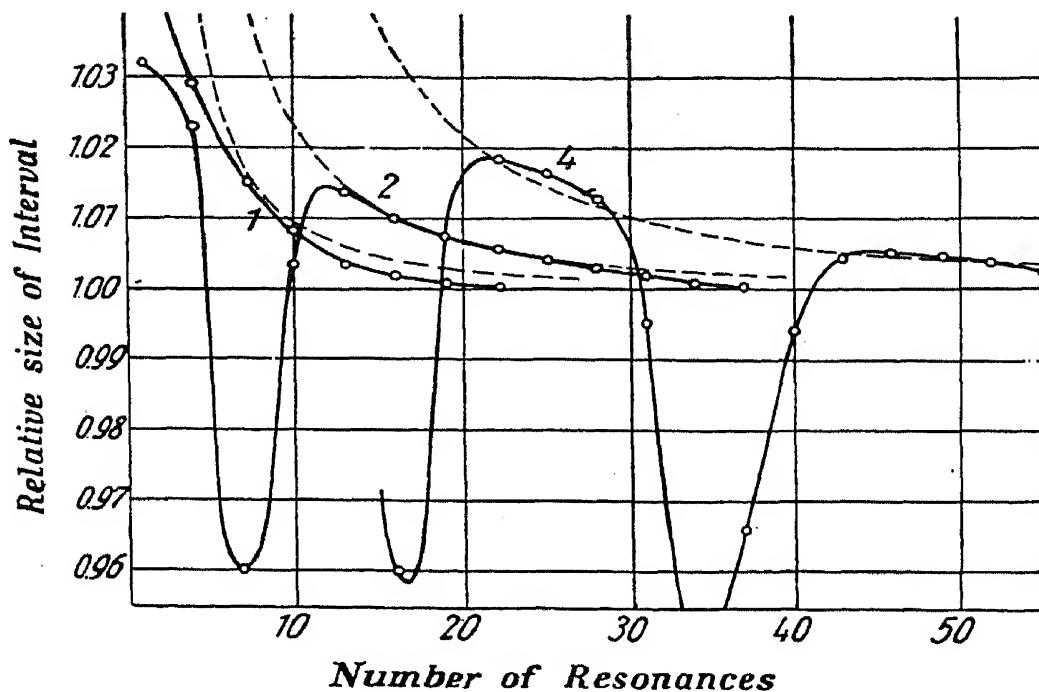


FIG. 95. Relative size of interferometer intervals, as a function of their number counted from the source. Full lines are measurements by Grabau, dotted by Grossmann.

have been observed on several sides (355, 377, 378, 253, 169). Fig. 95 shows the measurements by Grabau of the relative sizes of the intervals plotted as a function of the number of the resonance position counted from the source, in this case circular with a radius  $R_s = 0.66\Lambda$ . Curve 1 was given by a circular reflector with radius  $R_r = 1.06\Lambda$ , curve 2 by  $R_r = 2.12\Lambda$ , and curve 4 by  $R_r = 4.24$ . We see that in case 1 close to the source the intervals are too great, and only assume the correct value from the twentieth onwards; with larger reflectors the intervals pass through one or several minima, finally approaching a limiting value. Grossmann (173) showed that this phenomenon is to be referred to diffraction of the sound waves at the source and reflector. Fig. 96 (a) and (b) shows the sound field of two circular piston

nembranes of radius  $R = 0.80\lambda$  and  $R = 1.75\lambda$ , calculated by Grossmann by putting numerical values into the solution, developed by Backhaus (14 and 15), of Rayleigh's formula for the velocity potential of points in the sound field of a piston membrane. The full lines represent the wave surfaces of the pressure wave;

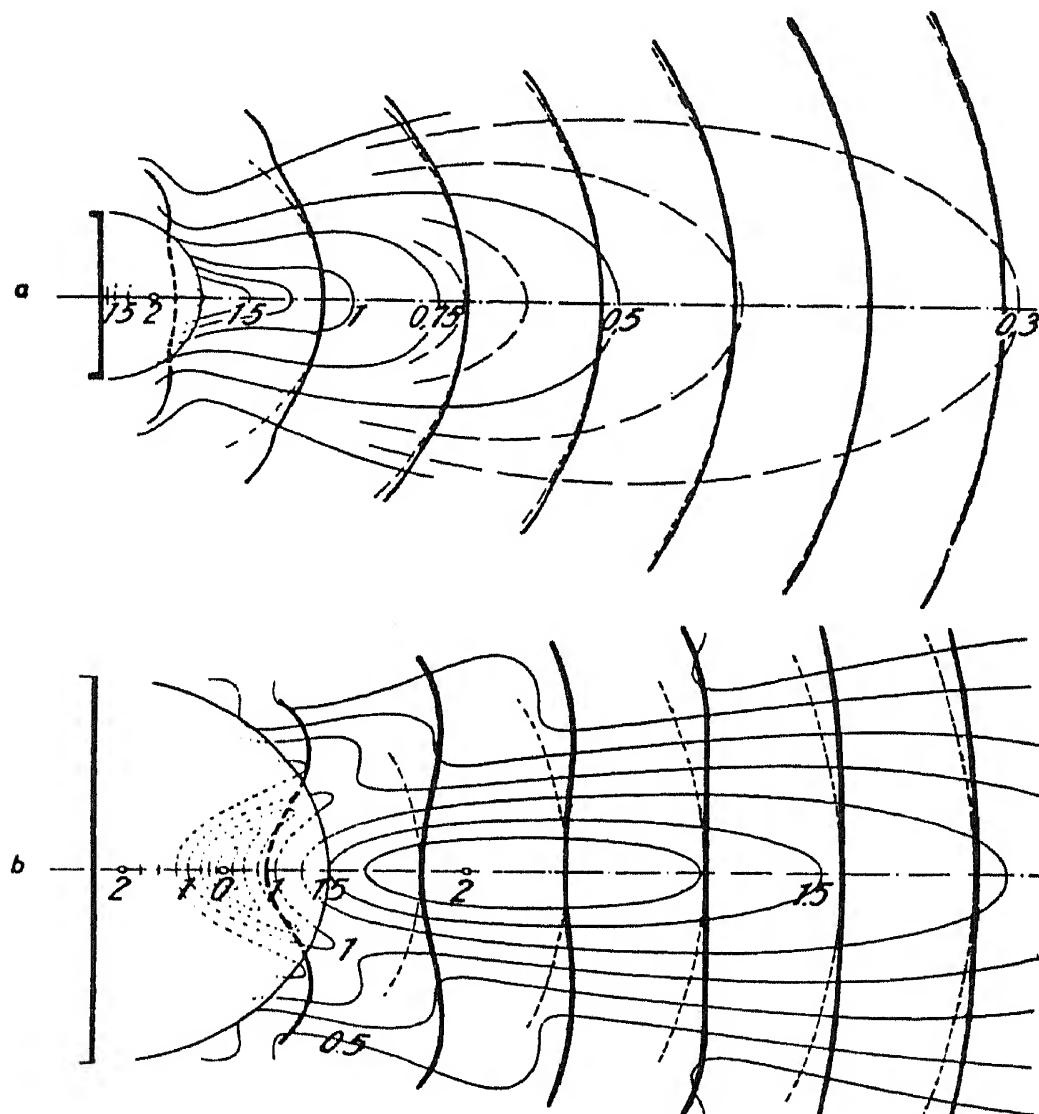


FIG. 96. Sound fields of a piston membrane: (a) radius  $0.80\lambda$ , (b) radius  $1.75\lambda$ .

the thin lines, which are dotted close to the source, represent surfaces of equal pressure amplitude, and thus give a picture of the radiation characteristic, which is more strongly marked in the case of the membrane large as compared with the wave-length, but where at the same time we get several subsidiary maxima of the sound radiation. The figures give the relation  $P/P_o$  where  $P_o = v\rho u$  ( $v$  = velocity of sound,  $\rho$  = density of medium in which the wave is formed, and  $u$  = velocity amplitude of the piston membrane). The wave fronts may be represented at great

distances from the vibrating membrane as spherical surfaces with the middle point of the membrane as centre, at least near to the axis, as may be seen by comparison with the circular arcs dotted in the drawing, but this is not the case close to the membrane, nor with membranes for which  $R > \Lambda/2$ . Here we even get the wave surface bent in the opposite direction, as is very beautifully seen in photographs (fig. 97) taken by Hiedemann and Asbach, by the

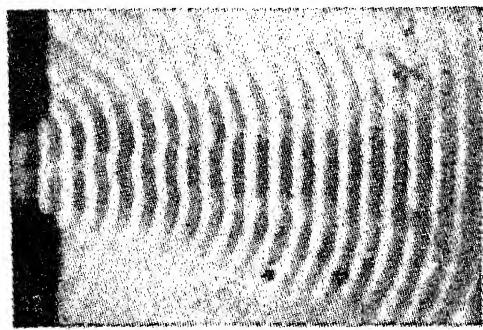


FIG. 97. Sound field of a rectangular piston membrane. Breadth of quartz = 4.85, frequency = 3300 kHz. (Hiedemann and Asbach).

method of secondary interferences, of the sound field in front of a vibrating quartz (breadth 4.85 $\Lambda$ , frequency 3300 kHz). Grossmann has shown that this behaviour of the wave surface may be used to interpret in the interferometer measurements the departures of the intervals from  $\Lambda/2$ , which are present when the distance between the source and the reflector is too small. Grossmann gives the following approximate formula for the size of the interval  $\Delta r$  in its dependence on the distance  $r \gtrsim n\Lambda$

( $n$  = number of the wave surface along the axis in front of the source) between source and reflector :

$$\Delta r = \frac{\Lambda}{2} \left( 1 + \frac{\frac{2R_r^2}{\Lambda^2} + \frac{5R_s^2}{\Lambda^2}}{16n(n+1)} \right)$$

We may, for example, calculate from this, given the size of the source and reflector for a certain wave-length, at what distance of reflector from source the intervals will be truly half a wave-length. The dotted curves in fig. 95 are calculated from this approximate formula and show good agreement between theory and experiment. Grabau gave a similar, but not so general, approximate formula for the same purpose in a special case. Experimental investigations of the propagation of sound from slits, diaphragms, and so on, are to be found also in the papers by Grossmann and Hiedemann (174) and also Boyle and his co-workers (83).

Pielemeier (358, 359), as well as Kao (243, 244) occasionally observed two sorts of intervals, that is to say, two systems of peaks in the anode currents, when making measurements with ultrasonic interferometers, the distance of the chief maxima giving a some-

what greater value for the half wave-length than the secondary maxima, which were named 'satellite' maxima. We are, however, still without a complete and unambiguous explanation of this phenomena; one interpretation is based on coupling effects between the whole source and the reflector, another on secondary frequencies of the quartz used.

In the interferometer arrangements so far described, the wavelength was found from the positions of the reflector at which there is maximum reaction of the sound wave on the quartz source; this is the case for distances between quartz and reflector which are multiples of half a wave-length, the whole space between the quartz and reflector being thrown into a sort of acoustical resonance. Yeagley (479, 480) has described an interferometer arrangement of a somewhat different sort, in which this condition of resonance is purposely avoided, making the method specially suitable for sound absorption measurements. In place of the reflector we have a receiving quartz inclined to the quartz source at such an angle that one of its edges is farther by  $\Lambda/3$  from the source than its opposite edge. The effect of this is that for every ray of sound which strikes the receiving quartz again after double reflection at receiver and source, a second sound ray exists which, likewise after two reflections, meets the receiving quartz in exactly opposite phase, so that the effect of the first ray is precisely neutralized, and no acoustical resonance is present. The acoustic energy taken up by the receiving quartz is sent as electrical energy to a two-valved amplifier connected to a valve voltmeter. At the same time, the oscillating circuit used for exciting the quartz source, and also quartz-controlled for the sake of the highest possible constancy, is made to supply to the receiver a further controllable amount of high-frequency energy. The valve voltmeter then gives us the vector sum of electrical and acoustical energy transmitted, the phase difference of which changes periodically with  $\Lambda$  as the distance between source and receiver is changed. The absence of resonance positions with the period  $\Lambda/2$  serves as a sensitive control for the correct adjustment of the apparatus and for the avoidance of acoustical resonance, as was already pointed out on p. 55.

We will now only mention a few further points which it is important to attend to in practical measurement. In the methods of Debye-Sears and Lucas-Biquard the wave-length of the sound

is determined by measurements of the angle of diffraction, and of the distances of the diffraction spectra from the central image of the slit. For this purpose either travelling or stationary sound waves may be used. The influence of the Doppler effect does not produce any noticeable disturbance on account of its smallness. The light source used is preferably good monochromatic light, as from a sodium lamp, or a mercury lamp with suitable filters or monochromators. When the angle of diffraction is to be determined directly, which operation may be done to an accuracy of about  $10''$  (18), no other magnitude is necessary for calculating the sound-wave length besides the wave-length of the light and the order number of the diffraction image. The accuracy of measurement then amounts to about  $1\%$ . If, on the other hand, the distances apart of the diffraction spectra are measured on a screen or a photographic plate, we require further for the calculation of the angle the distance of the image plane from the diffracting sound waves. If the optical arrangement of fig. 60 is used, that is to say if truly parallel light is sent through the sound wave, the distance between image plane and diffraction grating is given by the focal length of the objective  $O_2$ , which may be determined with sufficient accuracy. If for any reason it is not possible to employ strictly parallel light (for example, when the diffracting sound wave is put between the screen and the objective forming an image of the slit on the screen) we may use as distance, with sufficient accuracy, that between the image plane and the middle of the sound wave, as Schaefer, Bergmann, and Goehlich (417) have shown. The most convenient method is to photograph the diffraction images and to measure their distances apart on the plate. Modern small film cameras have here given excellent service for long series of measurements. Bergmann and Jaensch (53) have in this way used a Leica camera to measure the velocity of sound in a great number of organic liquids. By using the Leica special reflex addition, or by putting a totally reflecting prism in the beam of light close in front of the camera, the diffraction images may be first observed by eye and focussed. Parthasarathy (346, 347) observed in a similar way the velocity of sound for a great number of liquids and mixtures of liquids.

As regards the generation of the sound waves in the liquid under investigation, it is generally speaking advantageous to generate the sound in a space separated from the measuring

liquid (53, 204). In this case we are fairly free from the formation of disturbing striations, and also from undesired heating effects, which are particularly strong close to the vibrating quartz; we are also able to observe electrically conducting liquids. It is frequently sufficient to cement the vibrating quartz to the outside of the trough in which the liquid under investigation is contained (18, 455). Regarding the most favourable thickness of wall to give the highest possible intensity of sound behind it, see p. 46. The local heating readily occurring with strong sound waves in a liquid, and almost always leading to blurring of the optical picture and to a to-and-fro motion of the diffraction images on the screen, may easily be avoided by stirring the liquid with a small propeller. Neither the optical image nor the diffraction process is affected by the rapid motion of the liquid.

Special arrangements are necessary for carrying out sound velocity measurements in liquids at very low temperatures, or in liquefied gases. The velocity of sound in liquid oxygen at atmospheric pressure was first measured by Bär (20). The apparatus used was described by Liepmann (289), fig. 98 shows the measuring vessel and the arrangement of the piezoquartz. The liquid gas is contained in the Dewar vessel B, which has a plane-parallel bottom. A quartz tube Q, closed at both ends by windows, passes into the liquid through a brass cap K, which closes the vessel D with a rubber ring. The tube has a holder for the piezoquartz P at its lower end, and ensures that the light entering from above and then diffracted by the sound wave shall undergo no disturbing reflection at the surface of the liquid gas, which is always in a state of disturbance and never free from impurities. By pumping off gas at the tube A the liquid gas may be farther cooled. The temperature is determined by measuring the vapour pressure on a manometer connected to B. Fig. 99 gives the change with temperature in the velocity of sound, measured in the way described, for liquid oxygen. At

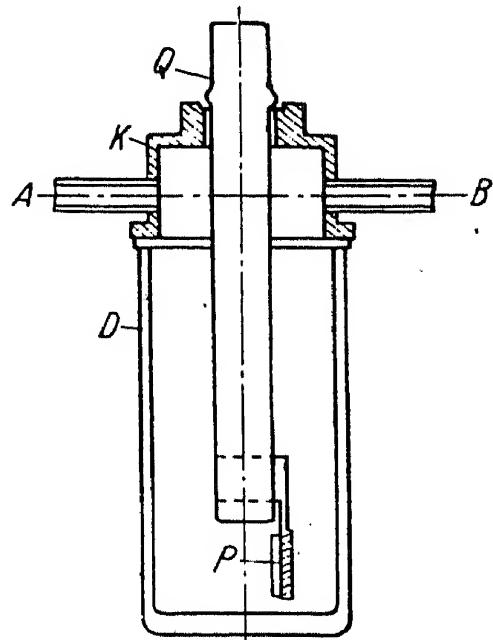


FIG. 98. Arrangement for measuring velocity of sound optically in liquid gases (Liepmann).

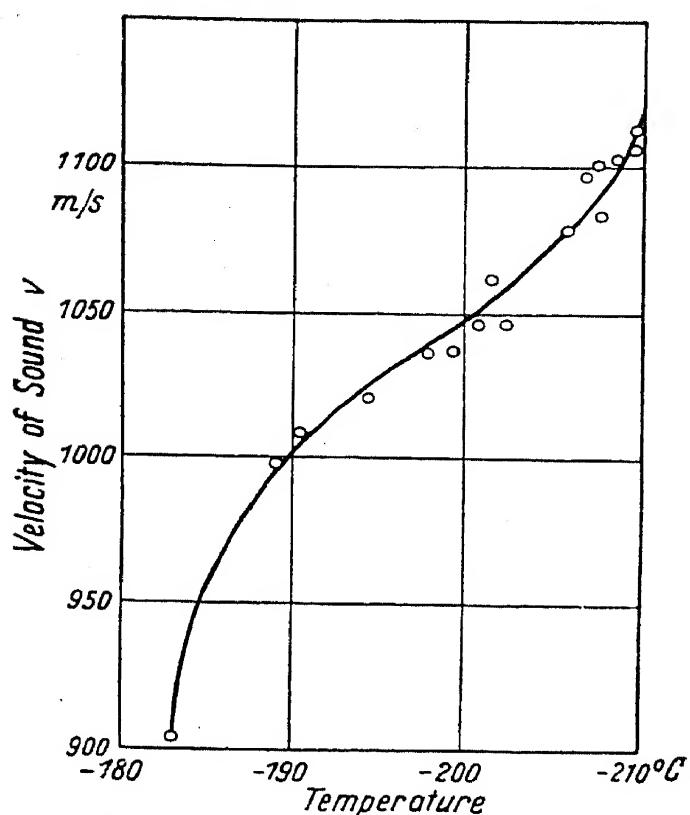
atmospheric pressure, that is to say at  $-186^{\circ}\text{C}$ ., the velocity of sound is 903 m/s. This gives us for the adiabatic compressibility  $\beta_{ad} 105.6 \times 10^{-6} \text{ atm}^{-1}$  (see also p. 112 and ref. 367).

The second optical method, worked out for precision measurements of sound velocity by Bachem and Hiedemann (7, 8, 10 *a*, 13), is based on observing directly the ultrasonic wave grating in the liquid by means of secondary interferences; with stationary sound waves, the half wave-length is measured directly (see p. 90).

The reading microscope and optical arrangement of fig. 81 are kept fixed, the measuring cell containing the liquid traversed by the sound wave is shifted by a comparator mechanism, the intervals between a great number of diffraction bands being measured. This may be done, according to the author, with an accuracy of 0.1 to 0.33 per cent. An advantage of the method is that white light may be used.

FIG. 99. Dependence of sound velocity in liquid oxygen on temperature (Liepmann).

If we have two liquids in separate layers, we are able to observe with one and the same sound frequency the system of bands in both liquids, and so carry out relative measurements with great accuracy, according to Sack (406). Care must be taken to ensure as great a constancy of temperature as possible in the liquid under investigation; more especially is it necessary to avoid any temperature gradient in the direction of the sound wave, since this results, even with parallel incident light, in a spurious widening of the band intervals of the sound-wave grating through the change in the index of refraction of the liquid with temperature. Fig. 100 shows a photograph of the ultrasonic grating close to the vibrating quartz, in which the widening of the band intervals is clearly seen. This increased distance apart of the wave fronts close to the quartz source with a standing wave corre-



ponds qualitatively to the change in interval in the ultrasonic interferometer discussed on p. 114; it is, however, quantitatively several times greater, as may be readily calculated by using Grossmann's approximate formula. The temperature gradient in front of the vibrating quartz may be as great as  $100^{\circ}$  per cm according to Bachem and Hiedemann (9).

A further source of error in this method of sound velocity measurements must be pointed out, arising from there being no truly stationary wave formed owing to want of parallelism between the quartz source and reflector. In this case also we get very bright and sharp bands parallel to the reflector, but these are the tracks of the parts of the amplitude maxima formed by the combination wave. As Bachem and Hiedemann (10) have shown, a faultless adjustment of sound source and reflector may be obtained by stroboscopic observations. When we have a true stationary wave, the bands must cover a considerable space without interruption even under stroboscopic observation. The method of Bergmann and Goehlich (51, 52), described on p. 96 for determining the direction of the wave front of travelling waves, may be used to set the piezoquartz and reflector.

Table VIII gives measurements of the velocity of sound in a great number of organic liquids at a frequency of  $7.36 \times 10^6$  Hz, and the adiabatic compressibility  $\beta_{ad}$  calculated from them, as measured by Parthasarathy (346, 347, 352). The temperatures at which the measurements were made, and the densities  $\rho$  of the liquids, and in some cases also the values of  $\kappa = C_p/C_v$  are given. The velocity of sound varies with the different liquids over a range of about 100 per cent. from 892 m/s for ethyl bromide to a maximum value of 1986 m/s for glycerine. The adiabatic compressibility lies between  $20.4 \times 10^{-6}$  for glycerine and  $147 \times 10^{-6}$  for pentane. If we attempt to find from these measurements a connection between the sound velocity and the substance investigated, or preferably, between compressibility and chemical constitution, we come upon a whole series of interesting points, of which only the most important will be given here; the original papers are given in the bibliography (53, 346, 347, 352).



FIG. 100. Photograph from which the temperature gradient in front of a quartz may be deduced (Bachem and Hiedemann).

TABLE VIII

*Velocity of Sound, Adiabatic Compressibility, and Ratio of the Specific Heats of Various Organic Liquids (Parthasarathy)*

Liquid	Chemical Formula	<i>t</i> °	<i>ρ</i>	<i>v</i> [m/s]	$\beta_{ad} \times 10^6$	<i>κ</i>
Acetal . . .	$\text{CH}_3.\text{CH}(\text{OC}_2\text{H}_5)_2$	24	1.030	1378	94	
Acetic acid ester . . .	$\text{CH}_3.\text{CO}.\text{CH}_2.\text{COOC}_2\text{H}_5$	25.5	1.021	1417	48.8	
Acetic anhydride . . .	$\text{CH}_3\text{CO} \begin{array}{c} \diagup \\ \text{O} \\ \diagdown \end{array} \text{CH}_3$	24	1.075	1384	48.6	
Acetone . . .	$\text{CH}_3.\text{CO}.\text{CH}_3$	22.5	0.791	1203	87.4	1.413
Aceto-dicarbonic-diethyl ester . . .	$\text{CO} \begin{array}{c} \diagup \\ \text{CH}_2.\text{COOC}_2\text{H}_5 \\ \diagdown \end{array} \text{CH}_2.\text{COOC}_2\text{H}_5$	22.5	1.085	1348	50.7	
Acetonitrile . . .	$\text{CH}_3.\text{CN}$	28	0.775	1275	52.2	
Acetophenone . . .	$\text{C}_6\text{H}_5.\text{CO}.\text{CH}_3$	24	1.024	1538	41.3	
Acetylene dichloride (cis) . . .	$\text{CHCl}.\text{CHCl}$	25	1.262	1025	75.4	
Acetyl tetrabromide . . .	$\text{CHBr}_2.\text{CHBr}_2$	28	2.962	1007	33.3	
Acetylene tetrachloride . . .	$\text{CHCl}_2.\text{CHCl}_2$	28	1.578	1155	48.6	
Adipic-diethyl ester . . .	$\text{CH}_2.\text{CH}_2.\text{COOC}_2\text{H}_5$	22	0.1866	1376	52.7	
Adipic-dimethyl ester . . .	$\text{CH}_2.\text{CH}_2.\text{COOC}_2\text{H}_5$ $\text{CH}_2.\text{CH}_2.\text{COO}.\text{CH}_3$	21.8	0.1994	1469	43.9	
Allyl chloride . . .	$\text{CH}_2\text{CH}.\text{CH}_2.\text{Cl}$	28	0.937	1088	90.1	
Amyl acetate . . .	$\text{CH}_3.\text{COO}.\text{C}_5\text{H}_{11}$	26	0.875	1168	83.8	
Amyl ether (iso) . . .	$\text{C}_5\text{H}_{11}.\text{O}.\text{C}_5\text{H}_{11}$	26	0.774	1153	97.2	
Amyl alcohol (n) . . .	$\text{CH}_3(\text{CH}_2)_4.\text{OH}$	24	0.8136	1347	67.8	1.323
Amyl formate . . .	$\text{H}.\text{COO}.\text{C}_5\text{H}_{11}$	26	0.869	1201	79.8	
Aniline . . .	$\text{C}_6\text{H}_5\text{NH}_2$	24	1.018	1682	34.7	1.302
Benzol . . .	$\text{C}_6\text{H}_6$	23	0.8725	1310	66.8	1.379
Benzoyl chloride . . .	$\text{C}_6\text{H}_5\text{COCl}$	28	1.211	1318	47.5	
Benzyl chloride . . .	$\text{C}_6\text{H}_5\text{CH}_2\text{Cl}$	28	1.102	1377	47.8	
Bromobenzol . . .	$\text{C}_6\text{H}_5\text{Br}$	28	1.495	1134	52.0	
Bromoform . . .	$\text{CHBr}_3$	23.5	2.889	929	40	
Butyl acetate (n) . . .	$\text{CH}_3\text{COOC}_4\text{H}_9$	26	0.871	1179	82.6	
Butyl alcohol . . .	$\text{CH}_3(\text{CH}_2)_3\text{OH}$	23	0.8082	1315	71.5	1.160
Butyl bromide (n) . . .	$\text{CH}_3(\text{CH}_2)_2\text{CH}_2\text{Br}$	28	1.272	1016	76.2	
Butyl formate . . .	$\text{HCOOC}_4\text{H}_9$	24	0.9066	1199	76.8	
Butyl iodide (n) . . .	$\text{CH}_3(\text{CH}_2)_2\text{CH}_2\text{I}$	28	1.616	959	67.3	
Carbon disulphide . . .	$\text{CS}_2$	23	1.258	1149	60.2	1.552
Chlorobenzol . . .	$\text{C}_6\text{H}_5\text{Cl}$	23	1.101	1302	53.6	
Chloracetic ethyl ester . . .	$\text{CH}_2\text{ClCOOC}_2\text{H}_5$	25.5	1.160	1234	56.6	
Chloracetic methyl ester . . .	$\text{CH}_2\text{ClCOOCH}_3$	26	1.232	1331	45.8	
Chloroform . . .	$\text{CHCl}_3$	23.5	1.487	1001	67.1	1.499

TABLE VIII—*continued*

Liquid	Chemical Formula	$t^\circ$	$\rho$	$v$ [m/s]	$\beta_{ad} \times 10^6$	$\kappa$
Cresol methyl ether .	$C_6H_4(CH_3)(OCH)_3$	26	0.976	1385	53.4	
Cyclohexane .	$C_6H_{12}$	23	0.7721	1257	81.9	
Cyclohexanol .	$C_5H_{10}CH(OH)$	23.5	0.9461	1622	40.2	
Cyclohexanone .	$C_5H_{10}CO$	23.5	0.9491	1441	50.8	
Cyclopentanone .	$C_4H_8CO$	24	0.9481	1474	48.6	
Cymol (para) .	$C_6H_4(CH_3)[CH(CH_3)_2]$	28	0.857	1308	68.2	
Decaline .	$C_{10}H_{18}$	27	0.875	1375	60.4	
Diethyl ketone .	$C_6H_5COC_6H_5$	24	0.8132	1314	71.2	
Dichlorethylene .	$CHCl.CHCl$	25.5	1.262	1025	75.4	
Dichlorobenzol (m) .	$C_6H_4Cl_2$	28	1.285	1232	51.2	
Dichlorobenzol (o) .	$C_6H_4Cl_2$	25	1.294	1246	49.7	
Diglycolic diethyl ester	$\begin{array}{c} CH_2COOC_2H_5 \\   \\ O \\   \\ CH_2COOC_2H_5 \end{array}$	22	1.433	1435	43.9	
Dimethylglutaric-dimethyl ester .	$\begin{array}{c} CH_2-COOCH_3 \\   \\ C(CH_3)_2 \\   \\ CH_2-COOCH_3 \end{array}$	24	1.038	1371	51.3	
Dioxane .	$C_4H_8O_2$	24	1.030	1378	51.5	
Dipentene .	$C_{10}H_{16}$	23.8	0.8644	1328	65.5	
Diphenylmethane .	$C_6H_5-CH_2-C_6H_5$	28	1.006	1501	35.1	
Ethyl acetate .	$CH_3.COOC_2H_5$	23.5	0.8989	1187	79	
Ethyl alcohol .	$C_2H_5OH$	23.5	0.7863	1207	87.3	1.214
Ethyl bromide .	$C_2H_5Br$	28	1.428	892	88.1	
Ethyl butyrate .	$C_3H_7.COOC_2H_5$	23.5	0.8768	1171	83.2	1.247
Ethylene bromide .	$CH_2Br$	24	2.178	1014	44.7	1.349
Ethylene chloride .	$\begin{array}{c} CH_2Br \\   \\ CH_2Cl \end{array}$	23	1.255	1240	51.8	
Ethylene glycol .	$\begin{array}{c} CH_2Cl \\   \\ CH_2-OH \end{array}$	24	1.103	1721	30.7	
Ethyl formate .	$H.COOC_2H_5$	24	0.9048	1263	69.3	
Ethyl phthalate .	$C_6H_4(COOC_2H_5)_2$	23	1.121	1471	41.2	
Ethyl propionate .	$C_2H_5COOC_2H_5$	23.5	0.8837	1185	80.6	
Glycerine .	$C_3H_5(OH)_3$	22	1.260	1986	20.4	1.33
Heptane .	$C_7H_{16}$	23	0.6812	1165	108.1	1.240
Hexane .	$C_6H_{14}$	23	0.6581	1113	122.7	1.214
Isoamyl ether .	$[(CH_3)_2CHCH_2CH_2]_2O$	23.5	0.7720	1180	93.0	
Isobutyl alcohol .	$(CH_3)_2.CHCH_2OH$	23.5	0.8011	1271	77.4	1.268
Isopropyl alcohol .	$CH_3CHOHCH_3$	23	0.785	1231	84.1	1.272

TABLE VIII—*continued*

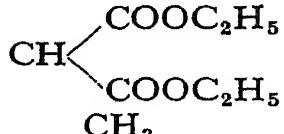
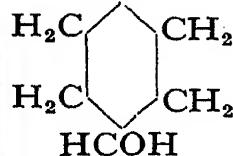
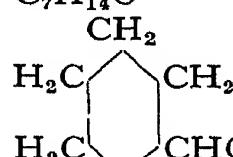
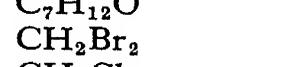
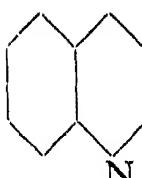
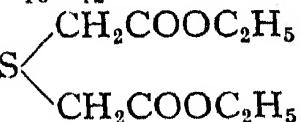
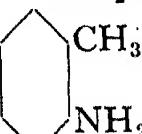
Liquid	Chemical Formula	$t^\circ$	$\rho$	$v$ [m/s]	$\beta_{ad} \times 10^6$
Malonic diethyl ester .		22	1.050	1386	49.6
Mesitylene . .		28	0.862	1320	66.6
Methyl acetate . .	$\text{CH}_3\text{COOCH}_3$	24	0.9282	1211	73.5
Methyl alcohol . .	$\text{CH}_3\text{OH}$	23.8	0.7921	1130	89.9
Methylcyclohexanol-o .		25.5	0.922	1421	53.7
Methylcyclohexanol-m	$\text{C}_7\text{H}_{14}\text{O}$	25.5	0.914	1406	55.3
Methylcyclohexanol-p .		25.5	0.920	1387	56.6
Methylcyclohexanone-o		25.5	0.924	1353	59.1
Methylcyclohexanone-p	$\text{C}_7\text{H}_{12}\text{O}$	25.5	0.913	1348	60.3
Methylene bromide .	$\text{CH}_2\text{Br}_2$	24	2.453	971	43.2
Methylene chloride .	$\text{CH}_2\text{Cl}_2$	23.5	1.336	1.064	66.2
Methylene iodide .	$\text{CH}_2\text{I}_2$	24	3.323	977	31.5
Methyl hexaline . .	$\text{C}_6\text{H}_{10}(\text{CH}_3)(\text{OH})$	22.5	0.913	1428	53.7
Methyl hexyl ketone .	$\text{CH}_3\text{COC}_6\text{H}_{13}$	24	0.8170	1324	69.8
Methyl propionate .	$\text{C}_2\text{H}_5\text{COOCH}_3$	24.5	0.9112	1215	74.3
Monochlornaphthaline	$\text{C}_{10}\text{H}_7\text{Cl}$	27	1.189	1462	39.3
Nitrobenzol . .	$\text{C}_6\text{H}_5\text{NO}_2$	24	1.199	1490	37.6
Octane . . .	$\text{C}_8\text{H}_{18}$	19	0.702	1238	94.2
Octyl alcohol (sec)	$\text{CH}_3\text{CHOH}(\text{CH}_2)_5\text{CH}_3$	26	0.818	1302	72.1
Oxalic diethyl ester .	$\text{COOC}_2\text{H}_5$	22	1.075	1392	48.0
Pentane . . .	$\text{C}_5\text{H}_{12}$	18	0.632	1052	147.2
Phenyl ethyl ether .	$\text{C}_6\text{H}_5\text{OC}_2\text{H}_5$	26	0.774	1153	97.2
Phenyl methyl ether .	$\text{C}_6\text{H}_5\text{OCH}_3$	26	1.138	1353	48.0
Phenyl mustard oil .	$\text{C}_6\text{H}_5\text{NCS}$	27	1.131	1412	44.4
Picoline ( $\alpha$ ) . .	$\text{C}_5\text{H}_4\text{NCH}_3$	28	0.9508	1433	49.9
Picoline ( $\beta$ ) . .	$\text{CH}_3\text{C}_5\text{H}_4\text{N}$	28	0.952	1419	52.2
Propylacetate . .	$\text{CH}_3\text{COOC}_3\text{H}_7$	26	0.891	1182	80.3
Propyl alcohol (n) .	$\text{C}_3\text{H}_7\text{OH}$	24	0.8011	1234	81.9
Pyridine . . .	$\text{C}_6\text{H}_5\text{N}$	24	0.9752	1448	48.9

TABLE VIII—*continued*

Liquid	Chemical Formula	$t^{\circ}$	$\rho$	$v$ [m/s]	$\beta_{ad} \times 10^6$	$\kappa$
Quinoline . . .		22	1.090	1643	34.0	
Resorcin dimethyl ether	$C_6H_4(OCH_3)_2$	26	1.054	1460	44.5	
Resorcin monomethyl ether . . .	$C_6H_4(OH)(OCH_3)$	26	1.145	1629	32.9	
Succinic diethyl ester .	$CH_2-COOC_2H_5$	22	1.039	1378	50.7	
	$CH_2-COOC_2H_5$					
Tertiary amyl alcohol .	$(CH_3)_2C(OH)C_2H_5$	28	0.809	1204	117.3	
Tetrabromomethane .	$CHBr_2CHBr_2$	28	2.962	1007	33.3	
Tetrachlorethane .	$CHCl_2CHCl_2$	28	1.578	1155	48.6	
Carbon tetrachloride .	$CCl_4$	23	1.596	928.5	72.6	
Tetrachlorethylene .	$C_2Cl_4$	28	1.623	1027	58.4	
Tetraline . . .	$C_{10}H_{12}$	24	0.9681	1465	48.1	
Thiodiglycolic diethyl ester . . .		22.5	1.142	1449	41.7	
Toluidine (o) . . .		22.5	0.994	1669	36.1	
Toluol . . .	$C_6H_5.CH_3$	23	0.8631	1320	66.5	1.345
Trimethylene bromide	$CH_2-Br$   $CH_2$   $CH_2-Br$	23.5	1.977	1144	38.6	
Water . . .	$H_2O$	24	0.9972	1494	44.9	
Xylol (m) . . .	$C_6H_4(CH_3)_2$	22	0.8612	1328	65.9	
Xylol (o) . . .		22	0.877	1352	62.4	
Xylol (p) . . .		22	0.858	1330	65.9	

In the case of the saturated hydrocarbons, as we see from Table IX, the velocity of sound increases with increasing carbon content; since the density changes only slightly, this means a decrease in compressibility.

## ULTRASONICS

TABLE IX

*Velocity of Sound and Adiabatic Compressibility of Saturated Hydrocarbons*

Liquid	Formula	$\rho$	$v$ [m/s]	$\beta_{ad} \times 10^6$
Pentane . .	$C_5H_{12}$	0.622	1052	147.2
Hexane . .	$C_6H_{14}$	0.658	1113	122.7
Heptane . .	$C_7H_{16}$	0.681	1165	108.1
Octane . .	$C_8H_{18}$	0.702	1238	94.2

A similar change is present in the case of the monohydric saturated alcohols, as we see from Table X.

TABLE X

*Velocity of Sound and Adiabatic Compressibility for Monohydric Saturated Alcohols*

Liquid	Formula	$\rho$	$v$ [m/s]	$\beta_{ad} \times 10^6$
Methyl alcohol .	$CH_3OH$	0.792	1130	98.9
Ethyl alcohol .	$C_2H_5OH$	0.786	1207	87.3
Propyl alcohol .	$C_3H_7OH$	0.801	1234	81.9
Butyl alcohol .	$C_4H_9OH$	0.808	1315	71.5
Amyl alcohol .	$C_5H_{11}OH$	0.813	1347	67.8

The reason in both cases is probably to be sought in the lengthening of the molecular chain. By contrast, the esters of acetic acid, for example, show a decrease in sound velocity and increase in compressibility, as shown by Table XI.

TABLE XI

*Velocity of Sound and Adiabatic Compressibility of the Esters of Acetic Acid*

Liquid	Formula	$\rho$	$v$ [m/s]	$\beta_{ad} \times 10^6$
Methyl acetate .	$CH_3COOCH_3$	0.928	1211	73.5
Ethyl acetate .	$CH_3COOC_2H_5$	0.898	1187	79
Propyl acetate .	$CH_3COOC_3H_7$	0.891	1182	80.3
Butyl acetate .	$CH_3COOC_4H_9$	0.871	1179	82.6
Amyl acetate .	$CH_3COOC_5H_{11}$	0.875	1168	83

Altogether, it is the spatial arrangement of the atoms in the liquid molecules that seems to play the decisive part in the velocity of sound and compressibility. Thus aromatic compounds always have a higher velocity of sound than aliphatic; for  $C_6H_6$ ,  $v = 1310$  m/s, while for  $C_6H_{14}$ ,  $v = 1113$  m/s. In the case of the benzol derivatives investigated, chlorobenzol, nitrobenzol, and aniline, both the density and the adiabatic compressibility increase in this order.

We see from the individual groups of Table XII that the compressibility decreases in the case of halogen compounds with increase in halogen contents; since the density at the same time greatly increases, the velocity of sound itself does not show a regular change.

TABLE XII

Liquid	Formula	$\rho$	$v$ [m/s]	$\beta_{ad} \times 10^6$
Monobromomethane .	$C_2H_5Br$	1.428	892	88.1
Dibromomethane .	$C_2H_4Br_2$	2.178	1014	44.7
Tetrabromomethane .	$C_2H_2Br_4$	2.962	1007	33.3
Methylenebromide .	$CH_2Br_2$	2.453	971	43.2
Bromoform .	$CHBr_3$	2.889	929	40.0
Benzol .	$C_6H_6$	0.872	1310	66.8
Chlorobenzol .	$C_6H_5Cl$	1.101	1302	53.6
Dichlorobenzol .	$C_6H_4Cl_2$	1.285	1232	51.2

If we replace the lighter chlorine ion by the heavier bromine or iodine ion, the compressibility falls, as we see from Table XIII.

TABLE XIII

*Velocity of Sound and Adiabatic Compressibility of some Halogen Compounds*

Liquid	Formula	$\rho$	$v$ [m/s]	$\beta_{ad} \times 10^6$
Chloroform .	$CHCl_3$	1.487	1001	67.1
Bromoform .	$CHBr_3$	2.889	929	40.0
Methylene chloride.	$CH_2Cl_2$	1.336	1064	66.3
Methylene bromide.	$CH_2Br_2$	2.453	971	43.2
Methylene iodide .	$CH_2I_2$	3.323	977	31.5

Further interesting facts are that in cases of position isomerism, the ortho-compound always shows the higher sound velocity and smaller compressibility, and that the velocity of sound is lowered by the presence of a double bond.

If two liquids with different sound velocities are mixed, that of the mixture lies between the values for the components singly; since the density and compressibility are changed by mixing, the connection between sound velocity and composition can only be represented by a straight line in a few cases. Measurements of this sort were carried out by Wilson and Richards (472) and Parthasarathy (348).

(b) **The Absorption of Sound in Liquids, and its Measurement.** The sound intensity  $J_0$  of a plane sound wave decreases in a liquid by passage over a distance  $x$  to the value  $J_x = J_0 e^{-2ax}$ , if  $a$  represents the absorption coefficient for the sound amplitude. The value of  $a$  is chiefly determined by the internal friction of the sound conducting medium. According to Stokes (444) the part due to internal friction is

$$a_r = \frac{8}{3} \frac{\pi^2 N^2 \eta}{v^3 \rho} = \frac{8}{3} \frac{\pi^2 \eta}{\Lambda^2 v \rho},$$

where  $N$  is the frequency of the sound,  $\Lambda$  its wave-length,  $v$  its velocity,  $\eta$  the coefficient of viscosity, and  $\rho$  the density of the medium. The viscosity is sometimes also measured by the kinetic coefficient of friction  $\mu$ , introduced by Maxwell, which is connected with  $\eta$  and  $\rho$  by the relation  $\mu = \frac{\eta}{\rho}$ . Since both  $\eta$  and also  $\rho$  and  $v$  are dependent on temperature,  $a_r$  is also a function of the temperature. For the relative change of  $a_r$  we get

$$\frac{da_r}{a} = \frac{d\eta}{\eta} - \frac{dp}{\rho} - 3 \frac{dv}{v}.$$

For water, for example,  $a_r$  decreases by about 3 per cent. for a rise of temperature of  $1^\circ$ .

The absorption of sound is also further caused by the thermal conductivity of the medium in which the sound waves travel; for the heat conducted from the compression points of the sound wave, which have a higher temperature than their surroundings,

to the latter, and to the expansion points of the wave, represents a loss of energy by the wave. According to Kirchhoff (248), the absorption coefficient due to conduction is given by

$$\alpha_l = \frac{2\pi^2 N^2}{v^3 \rho} \frac{\kappa - 1}{c_p} K = \frac{2\pi^2}{\Lambda^2 v \rho} \frac{\kappa - 1}{c_p} K,$$

where  $K$  is the thermal conductivity and  $\kappa$  the ratio of the specific heats. By using well-known thermodynamic relations, this equation may be transformed into the following:

$$\alpha_l = \frac{2\pi^2 N^2 K T \alpha^2}{\rho v W c_p} = \frac{2\pi^2 v K T \alpha^2}{\Lambda^2 \rho W c_p},$$

where  $\alpha$  is the thermal coefficient of expansion at constant pressure,  $W$  the mechanical equivalent of heat, and  $T$  the absolute temperature.

The complete absorption coefficient  $\alpha$  may therefore be represented by the equation

$$\begin{aligned} \alpha \approx \alpha_r + \alpha_l &= \frac{2\pi^2 N^2}{v^3 \rho} \left( \frac{4}{3} \eta + \frac{\kappa - 1}{c_p} K \right) = \frac{2\pi^2}{\Lambda^2 v \rho} \left( \frac{4}{3} \eta + \frac{\kappa - 1}{c_p} K \right) \\ &= \frac{2\pi N^2}{v^3 \rho} \left( \frac{4}{3} \eta + \frac{K T \alpha^2 v^2}{W c_p} \right) = \frac{2\pi^2}{\Lambda^2 v \rho} \left( \frac{4}{3} \eta + \frac{K T \alpha^2 v^2}{W c_p} \right). \end{aligned}$$

It is important that  $\alpha$  increases with the square of the sound frequency, hence the value of  $A = \alpha/N^2$  is frequently given as the magnitude characteristic for sound absorption. Table XIV, due to Biquard (65), gives the values of  $\alpha/N^2$  for a number of liquids, as well as the parts due to viscosity and conductivity respectively (see next page).

We see that the latter part contributes very little to the absorption. For water at 100 kHz we have  $\alpha = 8.5 \times 10^{-7}$ , that is to say the distance after passage of which the sound intensity has declined to the  $e$ -th part amounts to  $\frac{1}{2\alpha} = 5.8$  km; this is about 1000

times the value for air. For this reason, ultrasonics are very well suited for sending signals under water, whereas they can hardly be made use of for this purpose in air, at any rate at the higher frequencies.

TABLE XIV

*Sound Absorption Coefficients ( $\times 10^{17}$ ) as calculated for different Liquids (Biquard)*

Liquid	$\times 10^{17}$		
	$a_r/N^2$	$a_i/N^2$	$a/N^2$
Acetone . .	6.54	0.5	7.04
Ether . .	8.48	0.49	8.97
Benzol . .	8.36	0.3	8.66
Chloroform . .	10.045	0.057	10.1
Ethyl acetate . .	7.95	0.31	8.26
Methyl acetate . .	6.34	0.44	6.78
Meta-xylool . .	8.13	0.24	8.37
Toluol . .	7.56	0.28	7.84
Water. .	8.5	0.0064	8.5

It is very frequently preferable to define the absorption, **not** by the value of  $A$  given by the equation  $J_x = J_0 e^{-2N^2 A x}$ , but by the absorption coefficient  $A'$  per wave-length, corresponding to the equation  $J_x = J_0 e^{-\frac{2A'x}{\lambda}}$ .  $\frac{1}{2A'}$  then gives the distance in wave-lengths passed over before the intensity is reduced by  $1/e$ .

Very few absorption measurements in liquids have been carried out. Biquard has made the most important contribution, and has also dealt with the problem in detail in a general review (65). One method used by Biquard (65) depends on measurement of the sound radiation pressure. According to what was said on p. 44, the sound radiation pressure  $F$  is proportional to the sound intensity, so that we have the relation:  $S_x = S_0 e^{-2ax}$ . In order to get  $a$ , it is therefore sufficient to measure  $S$  for a wave travelling in the liquid under investigation at different distances  $x$  from the source, then to plot the straight line  $\ln S_x = \text{const.} - 2ax$ , and to determine  $a$  from the slope of this line. Biquard measured the sound radiation pressure by using the torsion pendulum described earlier in this work. It is important for these measurements that no stationary waves should be formed between the vane of the pendulum and the source of sound. In order to avoid this, it is generally sufficient to set the vane of the pendulum in its position of rest at a slight inclination to the incident wave front of the sound. We have further to take care that the torsion pendulum

is always exactly in the sound ray at different distances from the source, the ray having usually a limited cross-section. In order to eliminate chance variations in the sound intensity, the measurement is carried out by measuring the deflection  $\delta_T$  of the torsion pendulum at every position  $x$  for different sound intensities, which are adjusted by varying the closeness of the coupling between the vibrating quartz and the electrical oscillating circuit, and controlled by one of the methods given on p. 38. If we then plot  $\delta_T$  against  $\delta_G$ , the deflections of the galvanometer of the source, which indicate the sound intensity, we get a straight line for every value of  $x$ . If we then take from this sheaf of straight lines the deflections  $\delta_T$  for the different values of  $x$  at a certain intensity of sound, and plot  $\ln \delta_T$  against  $x$ , the slope of this line gives the required value of the absorption coefficient. A source of disturbance in these measurements are the unidirectional liquid currents proceeding from the quartz (see p. 47), their effect being added to that of the radiation pressure on the torsion pendulum. With very strongly absorbing liquids we have, at greater distances from the source, a further motion of the liquid, the cause of which is to be sought in the steep gradient of sound radiation pressure caused by the absorption. Biquard gives two ways of eliminating these disturbances in absorption measurements. One consists in putting close in front of and behind the torsion pendulum thin films of collodion, celluloid, or the like, which stop the unidirectional flow of the liquid, but transmit the sound vibrations. The other is to measure the radiation pressure ballistically with the torsion pendulum, the source of sound being turned on for a very short period only, say  $1/5''$ . We find then that the liquid current requires a certain time for its formation, so that it no longer disturbs ballistic measurements of the radiation pressure. The sound energy radiated in the short period may be registered by a valve voltmeter coupled to the vibrating quartz. Further details of the experimental arrangement and the manner of conducting the measurements are to be found in Biquard's papers (65).

Quite recently, Sörensen (437) has determined the absorption coefficients of different liquids, and used for sound intensity measurements the pressure balance described on p. 47. The decrease in sound pressure over a distance of 66 cm was measured, the results being quite reproducible. The liquids investigated

were water (0.022 ; 0.014) transformer oil (0.022 ; 0.020), glycerine (0.017), alcohol (0.027), toluol (0.014), xylol (0.011), acetone (0.012), benzol (0.016) ; the figures added in brackets give the absorption coefficients found experimentally at a frequency of 950 kHz. In the case of water and transformer oil, the first value refers to a sample which had not been degassed, the second to a liquid which had been boiled out thoroughly. The measured values of the absorption coefficients are considerably higher than those calculated by the theory of Stokes and Kirchoff ; this agrees with the values of Biquard given on p. 133. Sörensen found in general, excepting in the case of water, an increase in absorption with increase of frequency in the range 194 to 950 kHz ; further, alcohol, toluol, and benzol exhibit a dependence of absorption on sound intensity. It is not impossible that this increase is caused by the formation of bubbles which are scarcely visible.

In measurements with the torsion pendulum, the disturbance of the propagation of the sound by the presence of the pendulum is a disadvantage. Biquard (63) therefore attempted to measure the sound absorption optically. It was already pointed out on p. 74, that the formation of diffraction spectra, when a sound wave is traversed by visible light, is dependent on the intensity of the sound waves. If we therefore arrange the experiment in such a way that the sound waves travelling in the liquid are traversed by a beam of light at different distances from the source of sound, the absorption coefficient may be determined from the intensity of the light diffracted. For this purpose, the optical system of fig. 60 is made to form through the sound waves travelling in the liquid an image of a slit on a screen  $S$ , which has an opening of equal size at the place where the image of the slit is formed. Behind this opening we have a photoelectric cell, which then only measures the light contained in the slit image of zero order. Where the light enters the trough with the sound wave we have a diaphragm, to ensure that the light traverses only a small region of the sound waves. If diffraction is produced by the sound wave, the photoelectric cell measures the difference between incident ( $I_0$ ) and diffracted ( $I$ ) light intensity. It may be shown that the following relation holds good :

$$\frac{I_0 - I}{I_0} = 1 - \frac{\theta}{\theta_0} = k J_0 e^{-2ax} = k' \delta e^{-2ax}.$$

Here  $\theta$  and  $\theta_0$  denote the deflections of the galvanometer connected to the photoelectric cell for incident light intensities and  $I_0$  respectively,  $J_0$  the intensity of sound at the quartz, the deflection of an indicator (thermogalvanometer) connected to the sound source, and  $k, k'$  constants. The inclination of the straight lines represented by the equation

$$\ln\left(1 - \frac{\theta}{\theta_0}\right) = \text{const} - 2ax$$

gives the required value of  $a$ .

In carrying out the experiment, the trough with the liquid and its travelling sound wave is displaced, the whole optical system remaining fixed in position. It is necessary to have the walls of the trough of liquid plane and parallel, and to move it exactly parallel, in order to avoid a change in the diffraction of the light caused by a change in the angle of incidence. It is further to be noted, that the intensity of the diffracted light is only proportional to the sound intensity for small values of the latter, since at higher intensities multiple diffraction takes place (p. 72), causing the light to be diffracted back from the diffraction spectra into the central image. Table XV gives the absorption coefficients  $a$  measured by the optical method by Biquard (64) for a number of liquids, the frequency being 7958 kHz; the calculated values are given for comparison.

TABLE XV

*Calculated and Measured Sound Absorption Coefficients of different Liquids*

Liquid	$t$	$\alpha \times 10^2$ Calculated	$t$	$\alpha \times 10^2$ Measured
Acetone . .	20	0.44	17	2
Benzol . .	20	0.54	17	58
Chloroform . .	20	0.66	18	30
Ether . .	20	0.57	18	3.5
Ethyl acetate . .	15	0.67	15	4.9
Metaxylol . .	20	0.78	20	4.7
Methyl acetate . .	20	0.53	17	6.9
Toluol . .	20	0.49	20	5.4
Water . .	20	0.538	20	1.6

The measured values are in every case greater, in some 100 times. The reason for this great divergence has not yet been explained. It is not improbable that certain molecular phenomena play a part, such as are particularly marked in the propagation of ultrasonic waves in gases. The absorption coefficients measured by Biquard have recently been confirmed by the measurements of Claeys, Errera, and Sack (111) by the radiation pressure method. These authors put the excessive absorption down to a sort of hysteresis of the adiabatic compressibility of the liquids in question. Lucas (295) points out that the excessive absorption coefficients may be brought about by a diffusion of the sound rays, the liquids in question behaving as regards the propagation of elastic waves much as turbid media behave towards light. As causes we may have the thermal density fluctuations, and also the tendency of the liquid molecules to arrange themselves in certain symmetrical groups, thereby producing a sort of anisotropy of the compressibility. Biquard (66) was actually able to observe in toluol a scattering of sound waves of this description by means of a special experimental arrangement. A theoretical calculation of the scattering of sound waves at very small liquid regions, having a compressibility other than the macroscopic has been put forward by Lucas (296, 297).

Exploratory measurements of absorption in liquids were further carried out by Wyss (477), who likewise used the diffraction method. Measurements of absorption in toluol, xylol, carbon tetrachloride, were carried out by Bazulin (16) by an optical photographic method, which in principle amounts to the arrangement of Biquard and Wyss; he also finds too high values for the absorption coefficients. Mixtures of vaseline and petroleum of different viscosity gave an approximate proportionality between absorption and viscosity.

A somewhat different method of sound absorption measurement by an optical device was proposed by Baumgardt (29). Considerations given by Lucas and Biquard (p. 80) show that parallel rays of light entering a plane sound wave in a direction exactly parallel to the wave front, converge, on account of the density distribution in the medium carrying the sound waves, to definite focal lines, which lie parallel to the wave front at a distance of the sound wave-lengths. The distance  $y_0$  of these

convergence lines from the incident plane of the light at the sound wave is

$$y_0 = 1.57 \frac{\Lambda}{2\pi} \sqrt{\frac{n_0}{\Delta n}},$$

the change of refractive index  $\Delta n$  is determined by the pressure change  $\Delta p$  produced by the sound waves in the liquid; we have

$$\Delta n = \beta_{ad} \Delta p \frac{(n_0^2 - 1)(n_0^2 + 2)}{8n_0}$$

and hence

$$y_0 = 1.57 \frac{\Lambda \sqrt{2}}{\pi} \frac{n_0}{\sqrt{\beta_{ad}(n_0^2 - 1)(n_0^2 + 2)}} \frac{1}{\sqrt{\Delta p}}.$$

If the convergence lines are then examined by a microscope with stroboscopic illumination when produced by a travelling sound wave at a distance  $x_1$  from the source, the intensity of sound emitted from the source being simultaneously measured, say, by the high-frequency current exciting it, it will be necessary when observing at another distance  $x_2$ , farther from the sound wave, to increase the sound intensity in order to get the convergence lines back into the same focal plane of the microscope. On account of the absorption, the pressure amplitude  $\Delta p$  in the sound wave decreases with increase of the distance  $x$ , and  $y_0$  increases. If  $J_1$  and  $J_2$  are the sound intensities measured at the source when the convergence lines are observed at distances  $x_1$  and  $x_2$ , we have

$$J_1 e^{-2ax_1} = J_2 e^{-2ax_2},$$

from which it follows that

$$a = \frac{1}{2(x_2 - x_1)} \ln \frac{J_2}{J_1} = \frac{1}{2(x_2 - x_1)} \ln \frac{\theta_2}{\theta_1},$$

where  $\theta_1$  and  $\theta_2$  are respectively the deflections of the instrument measuring the intensity of the source. It remains to be seen how far this interesting method will prove to be of value, for so far no practical measurements have been made with it.

We may finally point out another method suitable for absorption measurements, to which Lucas (294) has drawn attention. If the sound wave is traversed parallel to the wave

front by a narrow beam of light, the dimensions of which in the direction of sound propagation are smaller than half the wave-length  $\Lambda$ , the light wave suffers a periodical deflection  $\theta$  on account of the density gradient in the sound wave; this deflection has the frequency of the sound, and its amplitude is given to a first approximation by the equation (67)

$$\theta = \frac{l}{n} \frac{2\pi}{\Lambda} = k \frac{l}{\rho v^2 \Lambda} dp,$$

where  $dn$  is the amplitude of the change in coefficient of refraction,  $dp$  the amplitude of the pressure change,  $l$  the length of the path of the light in the sound wave,  $\rho$  the density,  $v$  the velocity of sound, and  $k$  a constant. Since  $dn$  and  $dp$  respectively are proportional to the intensity of the sound, the possibility exists of determining the absorption coefficient by measuring  $\theta$  at different distances  $x$  from the source of sound; for  $l=6$  cm and a middle intensity of sound,  $\theta$  is of the order of  $1^\circ$ . Measurements by this method have not yet been carried out.

The dependence on temperature of sound absorption in water between  $18^\circ$  and  $40^\circ$ , due to the temperature dependence of the viscosity, was determined by Baumgardt (30), who used the optical method developed by Biquard. The decrease in absorption over the interval in question is about 70 per cent., which agrees well with the value calculated theoretically. Sørensen (438), who likewise investigated the temperature dependence of the absorption coefficient  $\alpha$ , finds for water a somewhat smaller decrease of absorption with rise of temperature, and for alcohol, toluol, and xylol a rise of  $\alpha$  with increase of temperature.

The measurements so far published certainly make it clear that the classical theory of sound absorption is not adequate to interpret the experimental results. The matter can only be cleared up finally by investigations over a larger range of temperature and frequency.

(c) The Velocity of Sound in Gases, and its Measurement. The velocity of sound in gases is determined, as in liquids, by the equation given on p. 104,

$$v = \sqrt{\frac{1}{\beta_{ad} \cdot \rho}} = \sqrt{\frac{\kappa}{\beta_{is} \cdot \rho}}.$$

Here  $\beta_{ad}$  and  $\beta_{is}$  are the adiabatic and isothermal compressibilities respectively,  $\rho$  the density, and  $\kappa = c_p/c_v$  = the ratio of specific heats. This equation is true for all gases, and allows the velocity of sound to be calculated from the adiabatic compressibility, and  $\kappa$  to be calculated when the isothermal compressibility is known from static pressure measurements. From the relation  $pV = \text{const.}$ , holding for an ideal gas, we find for  $\beta_{is} = \frac{1}{V} \left( \frac{\partial V}{\partial p} \right)_{is}$  the relation

$$\beta_{is} = \frac{1}{p} \quad \text{and so} \quad v = \sqrt{\frac{p \cdot \kappa}{\rho}}.$$

This is Laplace's equation for the velocity of sound in gases.

Using the gas equation  $pV = RT$ , and the relation  $M = \rho V$ , where  $V$  is the molecular volume,  $M$  the molecular weight,  $T$  the absolute temperature, and  $R$  the gas constant, we get the relation

$$v = \sqrt{\frac{RT\kappa}{M}}.$$

In deducing this equation the propagation of sound is taken as an adiabatic phenomenon. But this is true, as Herzfeld and Rice (199) and also Condon (116) have shown by simple calculation, only as long as the wave-length of sound is not of the order of magnitude of the mean free path of the molecule ( $\approx 10^{-5}$  cm), that is to say, that the frequency of the sound in air is not higher than  $10^8$  Hz. Since the maxima and minima of temperature distribution in a sound wave are half a wave-length apart, a sensible temperature effect only appears, as may be shown by the theory of conduction, when the sound wave-length is of the order of the mean free path of the molecule. The adiabatic process then becomes more and more isothermal, and we then have for the velocity of sound Newton's equation

$v = \sqrt{\frac{p}{\rho}} = \sqrt{\frac{RT}{M}}$ , which is also true for very slow motion. No experiments have yet been made with these very high frequencies in gases.

The measurement of sound velocity in gases makes possible the determination of the ratio of the specific heats  $\kappa$  by means

of the equation  $v^2 = \frac{RT}{M}\kappa$ . This equation is, however, only true for ideal gases. If the boiling-point of the gas is higher than  $-150^\circ\text{ C.}$ , it is necessary in exact measurements to take account of departure from ideal behaviour, and we have the formula

$$v^2 = \kappa(RT + 2Bp)/M,$$

where  $B$  is the 'second virial coefficient,' which is dependent on the temperature.\*

Reduction of  $\kappa$  to pressure  $p = 0$ , that is to say, to the ideal condition, may be made by the equations

$$\begin{aligned} c_p - c_v &= (\kappa - 1)c_v = R + 2p \frac{dB}{dT}, \\ c_v^0 &= c_v + p \left( 2 \frac{dB}{dT} + T \frac{d^2B}{dT^2} \right), \\ c_p^0 &= R + c_v^0; \quad \kappa^0 = \frac{c_p^0}{c_v^0}. \end{aligned}$$

If a mixture of two gases I and II is under investigation, and the ratio of its specific heats has been determined by the velocity of sound at pressure  $p$ , we may first of all again calculate  $\overline{c_v^0}$  for the gas mixture, but using mean values for  $M$  and  $B$ . We then get

$$\overline{c_v^0} = (1 - g)c_{vI}^0 + gc_{vII}^0,$$

where  $g$  is the molecular fraction of the added gas II.  $g$  gives the composition of the mixture in terms of the relation of the number of molecules of one component to the total number of molecules. According to whether  $c_{vI}^0$  or  $c_{vII}^0$  is known, the measurement of  $\overline{c_v^0}$  for the gas mixture allows of the determination of the specific heat of the other gas.

The above equations for the velocity of sound in gases do not lead us to expect any dispersion of the velocity. Furthermore, when the absorption caused by viscosity, conduction, and radiation are taken into account as calculated from the classical formulæ of Stokes and Kirchhoff (see p. 128), the dependence of velocity on frequency works out as too small to be determined by the present methods of measurement.

\* See, for example, Eucken, *Grundriss d. phys. Chemie*, 4th ed., p. 40.

It is therefore all the more curious that Pierce (361) found for the first time in 1925, by interferometer measurements in  $\text{CO}_2$ , an increase of sound velocity with increase of frequency ; according to his measurements,  $v = 258.8 \text{ m/s}$  at 42 kHz,  $258.9 \text{ m/s}$  at 98 kHz, and  $260.2 \text{ m/s}$  at 206 kHz. This very interesting phenomenon may be explained by the assumption that at the higher ultrasonic frequencies the interchange of translational and vibrational or rotational energy of the gas molecules no longer keeps pace with the rapid oscillations of pressure ; in other words, the oscillatory degrees of freedom have no longer time in these rapid acoustic vibrations to adapt themselves completely to the adiabatic changes of temperature. But this means a decrease of the specific heat for the periodic process of the sound wave, for the same addition of energy now causes a greater increase of energy of translation, and hence of temperature. If  $E$  denotes the total energy,  $E_a$  the translational or external energy of the gas molecules, and  $E_i$  the total remaining energy of the internal degrees of freedom, we have

$$c_v = \left( \frac{\partial E}{\partial T} \right)_v = \left( \frac{\partial E_a}{\partial T} \right)_v + \left( \frac{\partial E_i}{\partial T} \right)_v = c_{va} + c_{vi}.$$

Here  $c_{va}$  denotes the specific heat of the translational degrees of freedom and  $c_{vi}$  that of the vibrational degrees of freedom, both at constant volume. We see that with increase of sound frequency when by our argument the vibrational energy no longer comes in,  $c_v$  must finally decrease to  $c_{va}$ .

Now the velocity of sound as given above is

$$v = \sqrt{\frac{p}{\rho}} \kappa = \sqrt{\frac{p}{\rho} \frac{c_p}{c_v}},$$

and since  $c_p - c_v = R$ , we have for  $v$  :

$$v = \sqrt{\frac{p}{\rho} \left( 1 + \frac{R}{c_v} \right)} = \sqrt{\frac{p}{\rho} \left( 1 + \frac{R}{c_{va} + c_{vi}} \right)}.$$

With increase of frequency, therefore,  $v$  must increase and finally reach the value  $v_\infty = \sqrt{\frac{p}{\rho} \left( 1 + \frac{R}{c_{va}} \right)}$ , when  $c_v$  is diminished by the amount of the heat of vibration.

Considerations of this kind were first put forward by Herzfeld

and Rice (199), who developed a dispersion formula for the sound velocity in gases taking account of viscosity, conduction, and interchange of translational and intramolecular energy. Kneser (252) then gave a detailed theory of the dispersion of sound, and obtained the following explicit dispersion formula for the velocity, neglecting viscosity and thermal conduction:

$$v = \sqrt{\frac{p}{\rho} \left( 1 + R \frac{c_v + \omega^2 \gamma^2 c_{va}}{c_v^2 + \omega^2 \gamma^2 c_{va}^2} \right)},$$

where  $\omega = 2\pi N$  is the angular frequency of the sound waves,  $c_v$  the molecular heat at constant volume, and the other terms have the same significance as before.  $\gamma$  then stands for the mean life of the energy quantum—that is to say, the time between the transformation of translational energy into a quantum of intramolecular energy and its retransformation into translational energy.  $\gamma$  is also sometimes named the adjustment time (*Einstelldauer*), or relaxation time, being defined by the equation

$$c_{vi}^t = c_{vi}^{st} \left( 1 - e^{-\frac{t}{\gamma}} \right).$$

Here  $c_{vi}^{st}$  denotes the full heat of vibration,  $c_{vi}^t$  the effective heat of vibration, when the gas is exposed to a temperature change in the very short time  $t$ .

It is easy to see that for  $\omega \rightarrow 0$ —that is to say, for small sound frequencies—the equation for the velocity goes over into the form

$$v_0 = \sqrt{\frac{p}{\rho} \left( 1 + \frac{R}{c_v} \right)},$$

which we gave above for the propagation for sound neglecting intramolecular processes, while for  $\omega \rightarrow \infty$  the velocity of sound tends towards the upper limit

$$v_\infty = \sqrt{\frac{p}{\rho} \left( 1 + \frac{R}{c_{va}} \right)}.$$

From  $v_0$  and  $v_\infty$  we deduce the relation

$$\frac{v_\infty^2}{v_0^2} = \frac{1 + \frac{R}{c_v - c_{vi}}}{1 + \frac{R}{c_v}},$$

which renders it possible, for example, to calculate the heat of vibration  $c_{vi}$  from the limiting values of the dispersion curve, and thus to determine which degrees of freedom are responsible for the dispersion of sound.

If the square of the velocity of sound is plotted, as is the usual practice, as function of  $\log N$ , we get the dispersion curve given in fig. 101, in this case for pure carbon dioxide; the points marked by circles are experimentally measured values of  $v$ . It follows at once from the course of the curve, that for carbon dioxide at  $\log N = 5.89$ , that is for  $N = 788$  kHz, the vibrational energy takes no part at all in the adiabatic changes of condition.

The dispersion curve has a point of inflection at

$$N_w = \frac{1}{2\pi\gamma} \frac{c_{va}}{c_v}.$$

By means of this relation the value of  $\gamma$  may be determined.

The slope of the dispersion curve at the point  $N_w$  may be calculated from the dispersion formula as

$$\left| \frac{dv^2}{d \log \omega} \right|_w = \frac{p R c_{vi}}{\rho 2 c_v c_{va}} = \frac{1}{2} (v_\infty^2 - v_0^2).$$

When a dispersion curve is obtained from a sufficient number of measurements,  $N_w$  may therefore be most simply determined by drawing a parallel to the axis of  $N$  between the limiting values  $v_0$  and  $v_\infty$  at a distance  $\frac{1}{2}(v_\infty^2 - v_0^2)$ , its intersection with the dispersion curve giving the value of  $N_w$ . But we may also determine for every measured value of  $N$  and  $v$  the value of  $N_w$  by means of the relation, derived from the dispersion formula,

$$N_w^2 = N^2 \frac{v_\infty^2 - v_0^2}{v^2 - v_0^2}$$

when  $v_0$  and  $v_\infty$  are both known.

Besides Kneser, Rutgers (401) has given a dispersion theory of sound, in which the gas traversed by the sound wave is considered as a mixture of two gases in an excited and a normal state

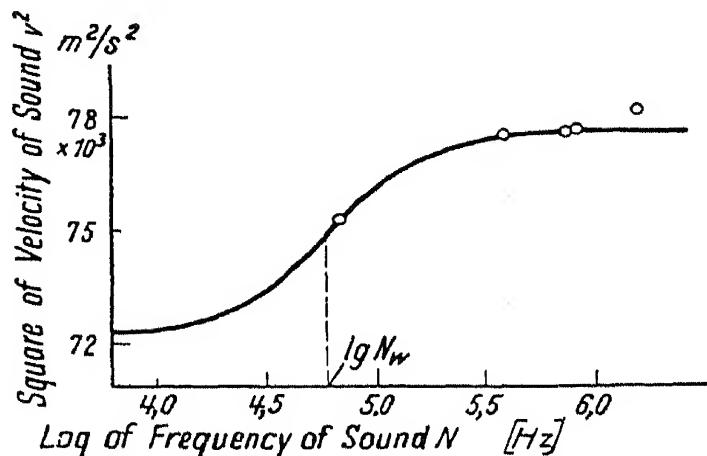


FIG. 101. Dispersion of sound in carbon dioxide (Wallmann).

respectively, in an exactly analogous manner to the theory given by Einstein (138) for the dispersion of sound in dissociated gases. He arrives at the same dispersion formula as Kneser (see also this author's remarks, 255). The same problem has further been treated by Bourgin (72 to 75) and Richards (383, 384), the latter for a gas having five groups of states of internal energy with different reaction times. It would take us too far to go into these interesting papers in detail. The foregoing discussion must suffice to show that the measurements of the sound velocity in gas are able to throw light on important intramolecular processes.

We already referred above to the determination of the relaxation time  $\gamma$ . By the aid of it, further constants  $k_{01}$  and  $k_{10}$  may be calculated, which are characteristic for the frequency of formation of a rotational or vibrational quantum (1), from translational energy (0). By quantum statistics, the following relation must exist between the excited molecules (number =  $n_1$ ) and the unexcited (number =  $n_0$ )

$$-\frac{dn_1}{dt} = k_{10}n_1 - k_{01}n_0.$$

In other words,  $1/k_{01}$  and  $1/k_{10}$  give the average time during which a molecule is in the normal and the excited state respectively.

$\gamma$  is connected with  $k_{01}$  and  $k_{10}$  by the relation  $\gamma = \frac{1}{k_{01} + k_{10}}$ .  $k_{01}$  and  $k_{10}$  may be calculated from this equation together with the relation holding for thermal equilibrium, that is to say for  $dn/dt = 0$  :

$$k_{01}/k_{10} = e^{-\frac{h\nu_0}{kT}}.$$

Here  $k$  is Boltzmann's constant,  $T$  the absolute temperature,  $h$  Planck's constant, and  $\nu_0$  = the natural frequency of the oscillator. If finally we introduce the efficiency of collision, defined as the ratio of effective collisions to the total number of collisions, we get from kinetic theory the collision efficiencies  $P_{10}$  and  $P_{01}$  for the excitation and destruction of a quantum in the case of like molecules :

$$P_{10} = k_{10}/a \quad \text{and} \quad P_{01} = k_{01}/a,$$

where

$$a = 2d^2 \left( 4\pi \frac{RT}{M} \right)^{1/2} (1 + ST),$$

$d$  being diameter of molecule of molecular weight  $M$ , and  $S$  Sutherland's constant for molecular attraction. The reciprocal values of  $P_{01}$  and  $P_{10}$  then give us the number of collisions necessary on the average for the generation and destruction respectively of a vibrational quantum.

We may take as example carbon dioxide, for which Pierce first determined the dispersion of sound. The first exact measurements of this gas were carried out by Kneser (251, 253). He found that the velocity of sound was sensibly constant for all frequencies up to about  $10^5$  Hz, and then increases by about 4 per cent., again becoming constant beyond  $10^6$  Hz. In the actual dispersion region, the velocity of sound increases by 1.6 per cent. per octave. The relaxation time is given, according to later measurements of Wallmann (459) and Eucken and Becker (139, 141), as  $5.7 \times 10^{-6}$  sec at  $18^\circ$  and 760 mm of mercury. This leads to the conclusion that about 67,000 collisions are necessary for the production of a vibrational quantum from translational energy, while the reverse transformation into translational energy takes place after no more than 51,000 collisions. If the value of the specific heat  $c_{vi}$  is calculated, which ceases to take part at high frequencies, we find, according to Kneser and Zühlke (261), the value 1.765. In the case of the linear carbon dioxide molecule we have two rotational degrees of freedom equal to one another and already fully excited at room temperature, as well as three natural frequencies of oscillation, the transverse or bending frequency, and two longitudinal frequencies, one of which makes no contribution to the specific heat at room temperature, and the other only the very small amount 0.142. Spectroscopical investigations in the infra-red give for the bending oscillation the value 1.690 for  $c_{vi}$ , in good agreement with that found by ultrasonic experiments. This is a proof that it is the elimination of the bending frequency from the specific heat which is responsible for the rise in the velocity of sound.

It may be pointed out here that the discussion so far has related to the case in which only one vibrational quantum is the cause of the elimination of part of the specific heat, and hence for the rise in sound velocity. In principle, namely, we should expect a region of dispersion for each natural frequency of the molecule, the single regions being also able to overlap.

The dependence on the pressure of the relaxation time of the

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ditional heat has been measured by Wallmann (469) for  $\text{CO}_2$ , an increase in inverse proportion to the pressure having been found him. The dependence on temperature was investigated by Eucken and Becker (141). A rise in specific heat with rise of temperature was found. The number of collisions necessary for removal of a quantum of energy from a vibrating molecule increases about fourfold in the case of pure  $\text{CO}_2$  when the temperature is raised from  $-32^\circ$  to  $+145^\circ$ . Other gases investigated are  $\text{CS}_2$  (386),  $\text{N}_2\text{O}$  (261, 142),  $\text{Cl}_2$  (141, 139),  $\text{CO}$  between 1000 and 1800 (328),  $\text{H}_2$  (260, 469, 142, 387),  $\text{N}_2$  (469), and  $\text{NH}_3$  (441).

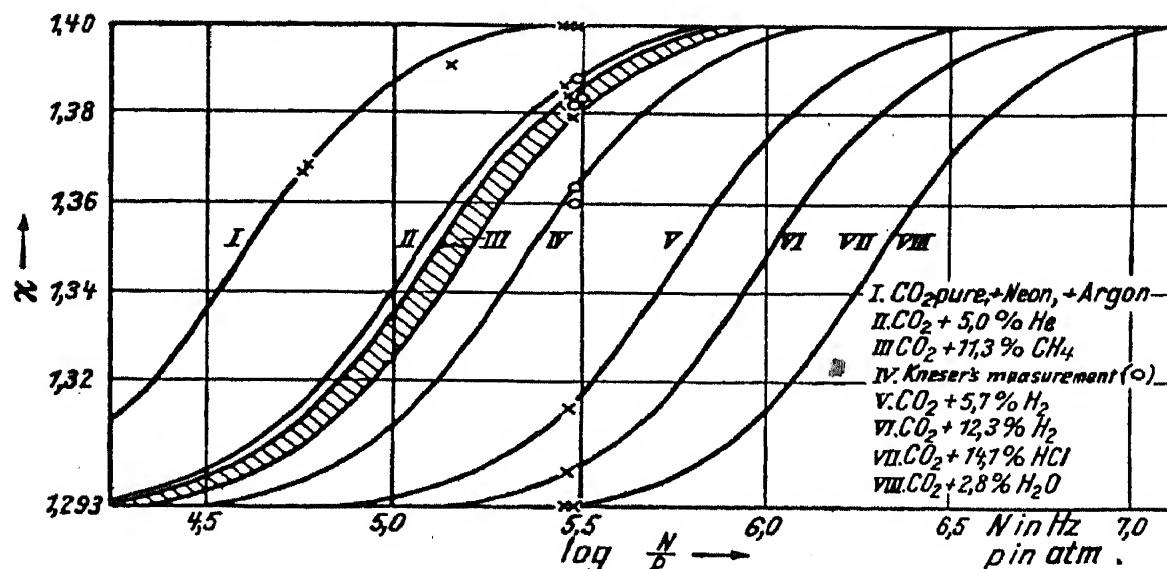


FIG. 102. Dispersion of sound in carbon dioxide with addition of other gases, at room temperature (Eucken and Becker).

her in the case of  $\text{H}_2$  or  $\text{N}_2$  could a dispersion of velocity be found in the range from 65 to 700 kHz, a fact in agreement with theoretical discussion (397, 398), though it would be outside the scope of this book to go into this point in detail.

Finally, we have a series of important investigations on sound dispersion in mixtures of gases, first undertaken by Richards and Eucken (387) for  $\text{C}_2\text{H}_4$  with additions of Ar, He,  $\text{N}_2$ , and  $\text{H}_2$ , and carried out with especial care by Eucken and co-workers (139, 141, 142), for  $\text{CO}_2$ ,  $\text{Cl}_2$ , and  $\text{NO}_2$ , also at different temperatures. In Fig. 102, the rise of  $\kappa$  is plotted against  $\log N/p$  for  $\text{CO}_2$ ,  $N$  being the frequency and  $p$  the pressure. While Ne and Ar have no influence, the addition of  $\text{H}_2$ ,  $\text{CH}_4$ , He,  $\text{HCl}$ , and  $\text{H}_2\text{O}$  cause a greater or less displacement of the dispersion curve in the direction of high frequencies. We see, for example, that at  $\log N/p = 5.3$ , corresponding to a frequency of 200 kHz, the part played by the

energy of vibration is already completely eliminated. Addition of 5 per cent. of He already lowers the values distinctly, and the normal statistical heat of vibration is attained with addition of 14.1 per cent. HCl. The cases of  $\text{Cl}_2$  and  $\text{NO}_2$  are similar. The addition of active foreign gases further results in a decrease of relaxation time, and the comparatively high number of collisions necessary to rob a vibrating molecule of an energy quantum is sometimes reduced very considerably by reactive foreign gas molecules. Wallmann (469) also investigated sound dispersion in  $\text{CO}_2$  with addition of foreign gases, and arrived at the same results. The velocity of sound in air with various amounts of moisture was measured by Ishii (232) over a range of frequency of 288 to 2890 kHz. Regarding the interpretation of this phenomenon we may mention the work of Franck and Eucken (149), who show that the frequency of transformation of translational into vibrational energy is very greatly, if not decisively, affected by the mutual disturbances of the electron systems of the colliding pair. Experiments show that the excitation of a molecule capable of vibration does not always depend upon the mass of the molecules striking it; no explanation can therefore be given from the standpoint of classical mechanics. The disturbance of the colliding molecules, and hence its influence on the change in sound velocity, is small in the case of such pairs as have hardly any, or only a small, chemical affinity for one another. It may, however, be multiplied up to 1000 times, when the colliding particles are able to react chemically with one another, though this does not mean to say that a change in chemical energy takes place in this process. Eucken and Becker (141) were able to show this most clearly by adding to  $\text{Cl}_2$  in one case  $\text{N}_2$  and in the other  $\text{CO}_2$ . The latter was about 100 times more effective than  $\text{N}_2$ , although the two gases are physically very much alike. Rough experiments further showed that a sensible change in the velocity of sound is produced in a mixture of  $\text{Cl}_2$  and  $\text{CO}_2$  when the chemical reactive power is modified, as by illumination.

Matters are still more in complex when we come to partially dissociated gases. Long before there had been any thought of the elimination of vibrational and rotational heat in sound propagation, Einstein (138) had already pointed out that a dispersion of sound must appear in a partly dissociated gas; for example, the dissociation equilibrium of nitrogen tetroxide,  $\text{N}_2\text{O}_4 \rightleftharpoons 2\text{NO}_2$ ,

will be continually displaced in the sound wave, since it depends upon pressure and temperature, assuming that the velocity of the reaction is great enough to follow the frequency of the sound. If, however, this is too high, the gas no longer changes its composition, and the elimination of the heat of dissociation results in a rise in sound velocity, from which the relaxation time of the velocity constant of the reaction may be measured. Grüneisen and Goens (175) sought in vain for a dispersion of sound in  $\text{N}_2\text{O}_4$  over the audible range up to 15 kHz, but Richards and Reid (385) found dispersion at 450 kHz and calculated from their results a velocity constant of  $5.3 \times 10^4$  for the dissociation of  $\text{N}_2\text{O}_4$  at  $25^\circ$  and 260 mm of mercury. It is, however, not yet decided, as pointed out by Teeter (460) among others, whether the dispersion effect found is to be ascribed to dissociation or to molecular energy of vibration.

As regards the technique of sound velocity measurements in gases, only interferometer arrangements call for consideration. Optical methods invariably give an insufficient degree of accuracy, for in the diffraction of light by ultrasonics in gases only the diffraction images of the first order are well formed, on account of the very small change of refractive index of pressure; and both the striation method and that of secondary interferences give comparatively feeble images, whereby the measurement of the sound wave-length is rendered much more difficult.

We will now describe some typical interferometer arrangements which have given good service in precision measurement, and have been especially developed for the measurement of the sound velocity in gases at different pressures and at high and low temperatures. Fig. 103 gives the section of a measuring system described by Kneser (253). The measurement of the wavelength is here effected by a Zeiss depth gauge, the measuring rod  $Ms$  of which carries at its lower end the reflecting disc  $R$ . This is large enough to cover three or four quartzes  $Q$  at the same time, which lie on a table resting on levelling screws. It is therefore possible to undertake the measurements at a number of frequencies without taking the apparatus apart or replacing any part of it. The reflector is raised and lowered by means of a two-cylinder float on mercury  $S$ , mercury being added or taken away by a siphon tube  $H$ , cemented through the plate  $T$  at the point  $A$ . Opening the tap  $H_1$  causes a rise, opening  $H_2$  a fall of the reflector.

In this way the reflector may be displaced continuously at any required rate. The position of the reflector is read by the microscope  $M$  to  $1/1000$  mm. The whole arrangement is under a glass bell jar, into which the gas to be investigated is introduced.

Zühlke (483) added a photographic recording device for this apparatus, whereby the displacement of the reflector and the deflections of the galvanometer were recorded simultaneously, the galvanometer indicating the consumption of electrical energy,

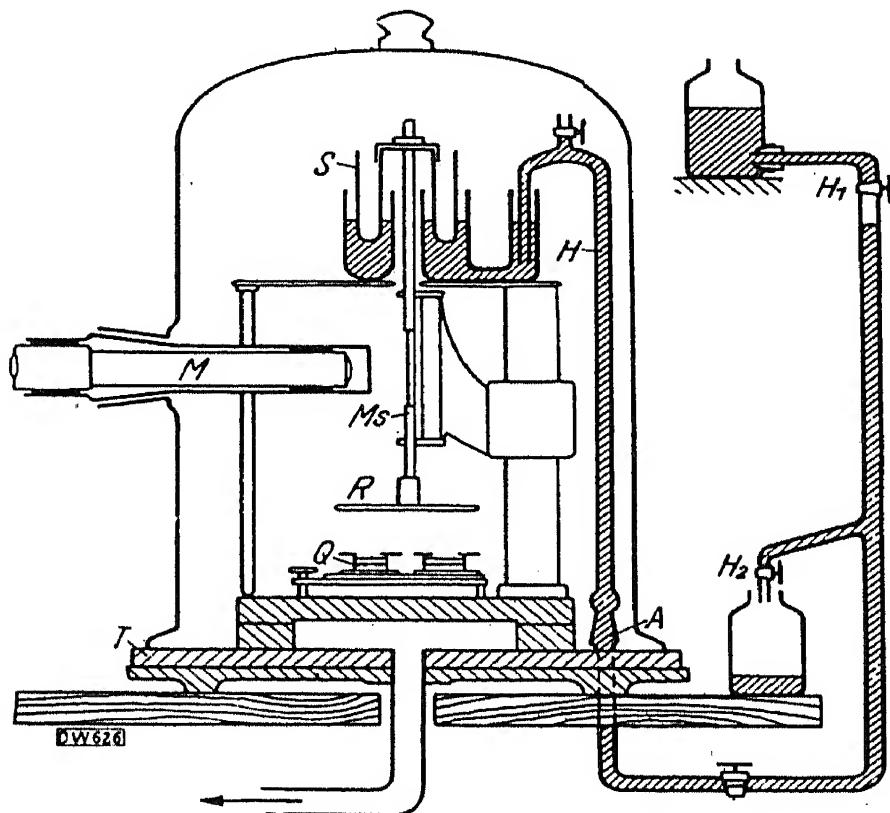


FIG. 103. Arrangement for measuring velocity of sound in gases (Kneser).

and hence the positions,  $\Lambda/2$  apart, at which there is maximum reaction of the reflector on the source. For this purpose the reflector  $R$  (fig. 104), displaceable vertically, and situated opposite the vibrating quartz  $Q$ , carries a glass scale divided in tenths of millimeters, which is illuminated by the source of light  $L_1$  through the prism  $P_2$  and the lens  $L_2$ , magnified 30 times by the microscope  $M$ , and projected as a row of dots on the photographic paper  $Ph$  by the cylindrical lens  $Z$ . If the paper is driven at about 30 times the rate at which the reflector is displaced, we get on it a system of parallel straight lines inclined at an angle of about  $45^\circ$ , and their points of intersection with the cross-wires of the microscope, which are photographed at the same time, form a scale on the

recording paper. At the same time, the deflections of the galvanometer  $G$  are recorded by means of the rays of light taking the path  $L_q - P_1 - L_1 - S$ ; the points of maximum reaction of the reflector on the vibrating quartz, and hence the half wave-length of the sound, may then be read off with great accuracy on the photographic record.

Fig. 105 gives an interferometer arrangement used by Eucken and Becker (140) for sound measurements in gases; the dimen-

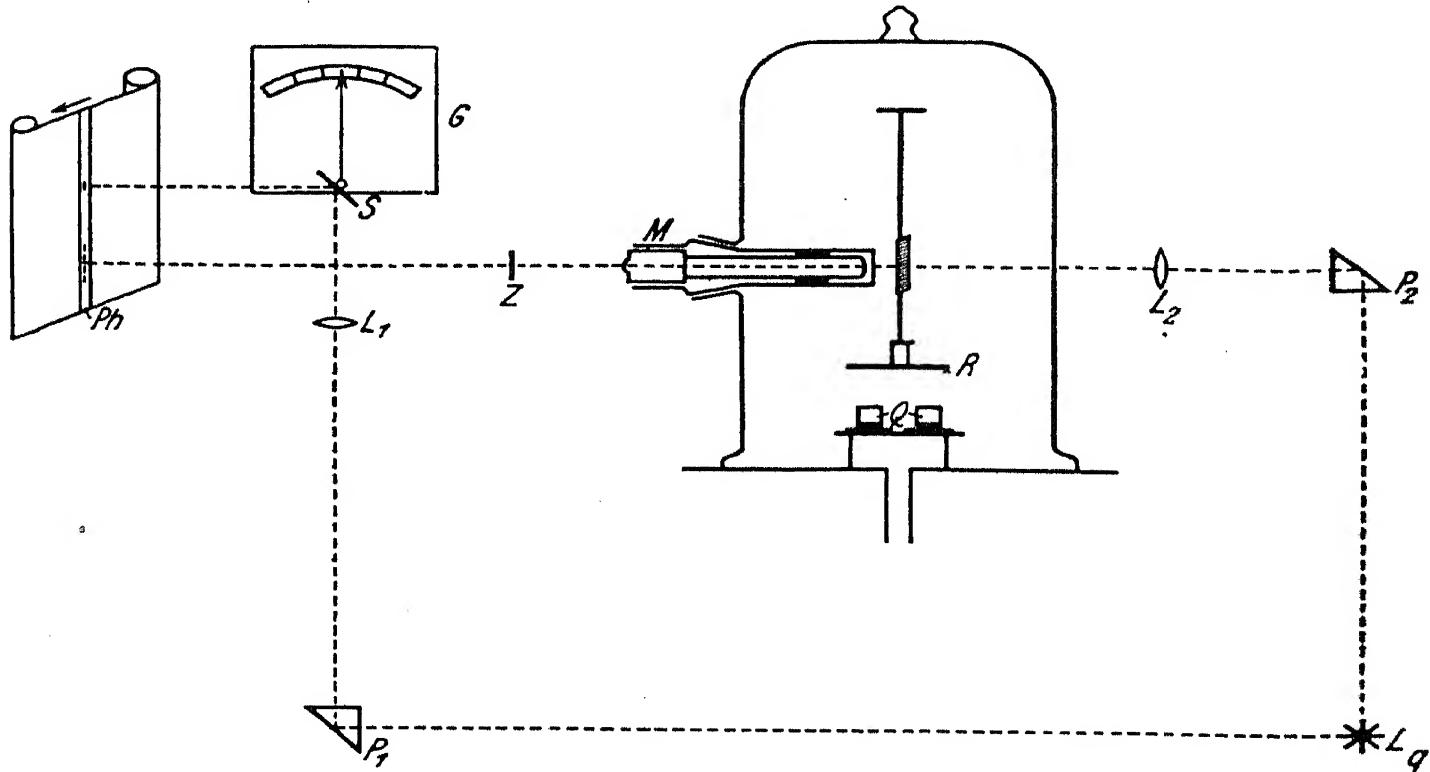


FIG. 104. Arrangement for recording interferometer resonance positions in measuring velocity of sound in gases (Zuhlke).

sions of this apparatus are kept within limits which allow of its being put into a Dewar vessel in order to make measurements at low as well as high temperatures. The reflector  $R$  in this case also is adjusted by being rigidly attached to a glass float  $W$ , resting on a mercury surface of variable height. The displacement of the reflector is determined by measurement of the mercury level in the graduated burette at the side. If a certain amount of the mercury ( $a$  cm<sup>3</sup>) is allowed to pass over into the float chamber, the reflector is raised by the amount  $x = a/q$ , when  $q$  is the area of the mercury surface in the float vessel. The two glass tubes  $a$  and  $b$  contain the wires conducting the current to the vibrating quartz  $Q$ ; the glass tube  $d$  serves to introduce the gas, which flows away by the tubes  $v$  and  $t$ , and may be sampled through

the tube *c* for analysis. The glass tube *g* joining the reflector to the float vessel *W* is made of Duran glass having a very small coefficient of expansion, a matter of great importance for measurements over a large range of temperature. When vessels of comparatively small cross-section are used, as is the case, for example, with the apparatus just described, disturbances frequently occur through reflection of sound waves at the walls of the vessel, especially in experiments with low ultrasonic frequencies, that is, long wavelengths; this leads to sound interference, and the galvanometer on the source frequently shows minima where nodes of the sound wave are not to be expected. These disturbances may generally be avoided by introducing suitable baffles. Fig. 106 shows a section of a baffle system used by Eucken and Becker and made up of conical funnels arranged one above the other, their effect being complete absorption of all sound waves striking the side walls.

Finally, we may describe shortly an apparatus used by Sherratt and Griffiths (428) for determining the velocity of the sound in gases up to a temperature of  $2000^{\circ}$ . Fig. 107 shows a section through the lower part of the apparatus. The sound waves pass from the quartz *Q* into a carbon tube *K*, in which the reflector *R*, likewise of carbon, may be displaced by measurable amounts.

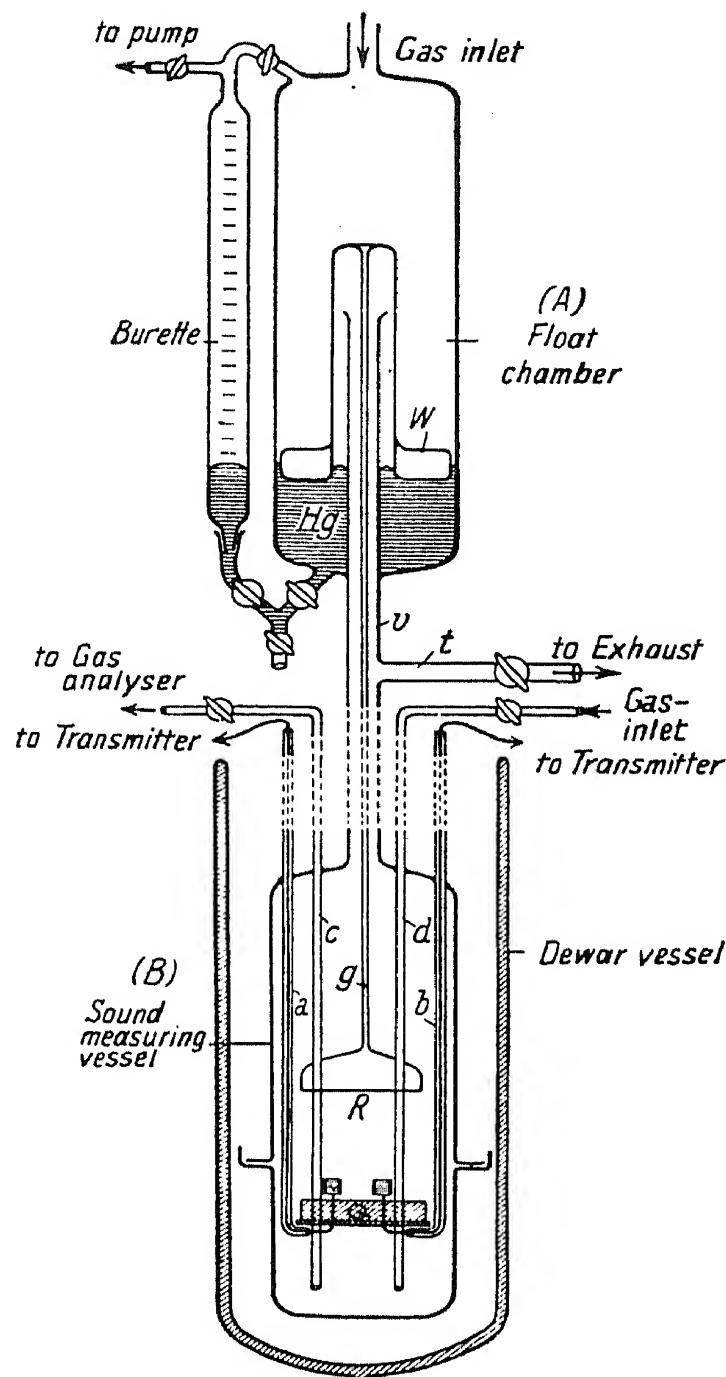


FIG. 105. Acoustical interferometer for sound velocity measurements in gases at low temperatures (Eucken and Becker).

The wave-lengths are determined in the usual way by determining the maxima of reaction on the quartz. The carbon tube  $K$  may be heated by an electric current, which is led from one end to the other of it. Fig. 107 shows only the lower connection for the current, formed by a massive aluminium electrode  $E$ , which is water-cooled and connected by the flexible  $L$  with the terminal  $A$ . A worm  $S$  carrying cooling water prevents radiation of heat downwards. Thermal insulation sideways is effected

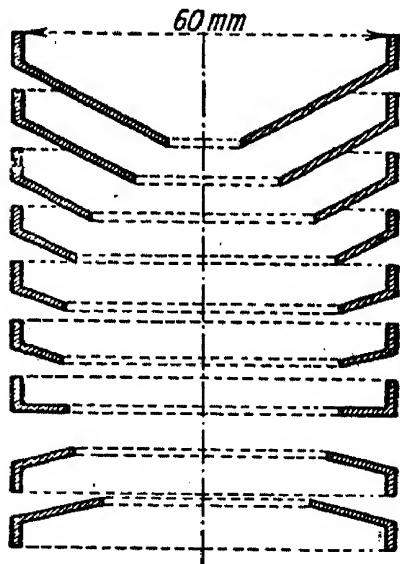


FIG. 106. System of diaphragms for sound.

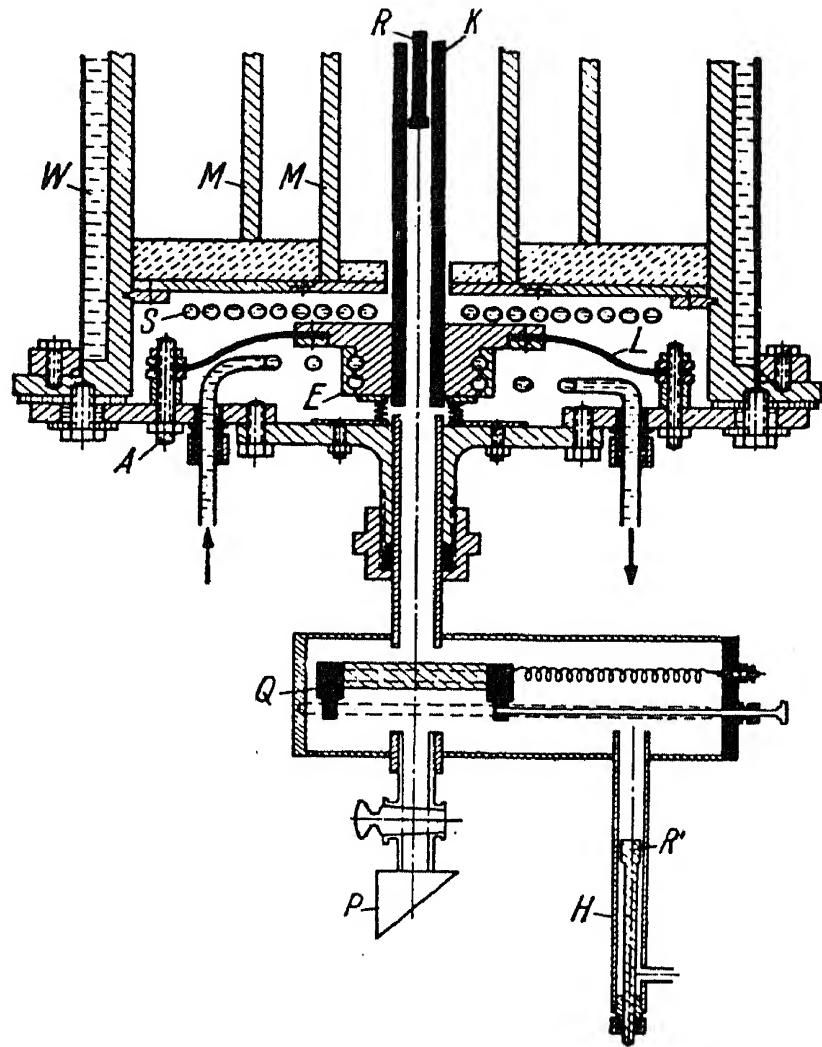


FIG. 107. Interferometer for measuring velocity of sound at high temperatures (Sherratt and Griffiths).

by a series of reflecting metal cylinders  $M$ , and the whole apparatus is surrounded by a water-jacket  $W$ . The temperature is measured by an optical pyrometer sighted on the carbon tube from below through the prism  $P$ . For this purpose the quartz  $Q$  is pushed aside. An accessory cylinder  $H$ , also provided with a movable reflector  $R'$ , allows of the velocity of sound being measured at the same time at the room temperature. Sherratt and Griffiths use this apparatus for measuring the specific heat of CO by the velocity of sound at temperatures between  $1000^\circ$  and  $1800^\circ$ , and found good agreement with values deduced from spectroscopical data.

Since the velocity of sound at constant frequency changes with the ratio of the two gases in the mixture, Griffiths (170) proposed to use an interferometer measurement of sound velocity to determine the relative proportions. This, however, is only possible in the case of gases which do not combine when mixed (see also ref. 28).

Table XVI gives the values for the velocity of sound in the case of a large number of gases and vapours.

TABLE XVI  
*Velocity of Sound in various Gases and Vapours*

Substance	$t$ [° C]	$c$ [m/s]	Substance	$t$ [° C]	$c$ [m/s]
Acetylene . .	0	327	Helium . .	0	971
Ammonia . .	0	415	Hydrobromic acid .	0	200
Amyl alcohol . .	136	218	Hydrochloric acid .	0	296
Argon . .	0	308	Hydriodic acid .	0	157
Benzol . .	80	208	Hydrogen . .	0	1261
Bromine . .	0	135	Illuminating gas .	13.6	453
Butyl alcohol (n) . .	116	235	Iodine . .	0	108
Carbon bisulphide . .	0	189	Iodine bromide . .	0	120
Carbonic acid . .	0	258	Mercury . .	360	208
Carbon monoxide . .	0	337	Methane . .	0	430
Carbon tetrachloride . .	77	150	Methyl alcohol . .	67	341
Chlorine . .	0	206	Nitric oxide . .	0	324
Chlorine iodide . .	0	135	Nitrogen . .	0	377.6
Chloroform . .	100	171	Nitrous oxide . .	0	257
Cyanogen . .	0	229	Oxygen . .	0	315.5
Ethane . .	10	308	Potassium . .	850	656
Ethyl acetate . .	76	208	Silicon fluoride . .	0	167
Ethyl alcohol . .	80	271	Sulphuretted hydrogen . .	0	289
Ethyl ether . .	0	176	Sulphurous acid . .	0	209
Ethylene . .	0	317	Water . .	0	401

(d) The Absorption of Sound in Gases, and its Measurement. Just as in liquids, the absorption of sound in gases depends, according to the classical theory, only on the viscosity and thermal conductivity, and the absorption coefficient  $\alpha$ , or  $A = \alpha/N^2$ , is determined by the same relation as given on p. 128 for liquids. The theoretical value of  $A$  for air is  $1.45 \times 10^{-13}$  cm/s—that is to say, about 1700 times greater than that for water at the same

frequency. It is to be noted that in the case of gases the part of the absorption dependent on thermal conductivity is not negligible as in liquids, but has the same order of magnitude as the part due to viscosity; for example, in the case of air  $\alpha_l \approx \frac{1}{3}\alpha_i$ . In mixtures of gases the mutual diffusion of the gas molecules may also produce an additional absorption, by reason of the lighter molecules being driven in the sound wave from positions of compression to positions of expansion. But this is equivalent to an irreversible transformation of energy into heat in the sound wave. A theoretical account of these processes has been given by Rocard (392); his discussion gives the absorption coefficient  $\alpha_D$ , depending on diffusion, as of about the same order as  $\alpha_l$ , and as increasing proportionally to  $N^2$ .

The first sound absorption measurements of value were made in air in 1911, that is to say about forty years after the theory had been given by Kirchhoff (240); they were carried out by Neklepajew (333) for a range of frequency from 132 to 415 kHz. Further measurements were subsequently made in different gases, up to the year 1931, by Pielemeier (357-360), Grossmann (171, 172), and Abello (1, 2). Their results are collected in Table XVII, which also gives the values of the sound absorption coefficient  $A = \alpha/N^2$  calculated from the classical theory.

TABLE XVII  
*Measured and Calculated Values of  
Sound Absorption Coefficients in different Gases*

Gas	Author	Frequency kHz	$10^{-13} \text{ cm}^{-1} \text{ s}^{-2}$	
			$\alpha/N^2$ Measured	$\alpha/N^2$ Calc. by Class. Theory
Air .	Neklepajew	132-415	2.94-3.99	1.45
	Pielemeier	1158-1408	1.67-1.99	1.45
	Grossmann	178	2.72	1.45
	Pielemeier	655-1219	3.47-1.90	1.78
	Abello	612	46.5	1.60
	Grossmann	64	277	1.60
$\text{O}_2$ .		99	540	1.60
		178	240	1.60
		612	0	2.0
$\text{CO}_2$ .				
Ar .	Abello			

With the exception of monatomic argon, the measured values are always higher than those calculated theoretically, in the case of  $\text{CO}_2$  as much as several hundred times; these measurements also show further that the value of  $\alpha/N^2$  is by no means independent of the frequency, as the classical theory requires.

We know to-day that the absorption of sound in polyatomic gases is conditioned by intramolecular processes, and that this molecular absorption of sound is in most cases considerably greater than according to the classical theory, so that we may in future neglect this in practice. The existence of sound dispersion in gases already requires, as we discussed in detail in the previous section, an especially strong absorption in the region of dispersion. We saw that the reason for the dispersion is chiefly to be found in the fact that the adiabatic compressions and expansions in the sound wave in the gas proceed so fast that the thermal equilibrium between excited and non-excited molecules is no longer able to be set up sufficiently quickly. In order to get a general idea of the absorption processes then taking place, we may make use of the following considerations put forward by Kneser (258). We take the temperature of the gas to be so high that the translational and rotational energies of the molecule are fully excited, and, further, that a certain number of molecules are, as regards their energy of vibration, in the first excited state—that is to say, possessed of one quantum of vibrational energy. If now we have at time  $t = t_0$ , as represented graphically in fig. 108, a sudden adiabatic compression, that is to say an access of energy, the translational and rotational energy immediately increases, whereas the energy of vibration only slowly adapts itself to the new condition (see the lower curve in fig. 108). The time which passes before the energy of vibration has approached the new value to the extent of  $1/e$  of the difference  $\Delta$  between the old and new value is determined by the relaxation time  $1/k_{10}$  (see also p. 142), where  $k_{10}$ , as defined in the previous section, gives the number of times

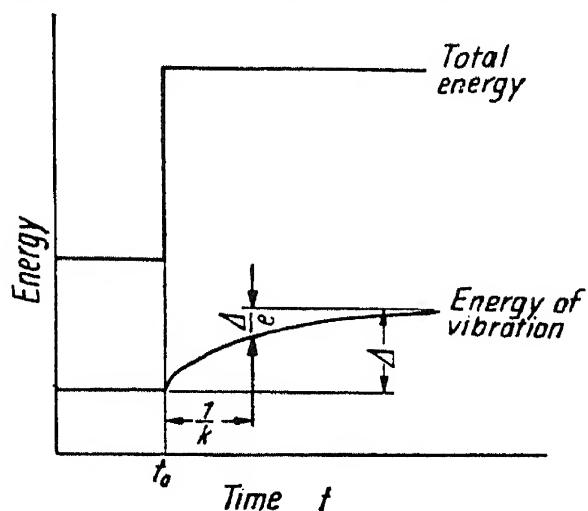


FIG. 108. Adaptation of vibrational energy to sudden adiabatic compression at  $t_0$  (Kneser).

that the energy of vibration has adapted to the new condition. The time which passes before the energy of vibration has approached the new value to the extent of  $1/e$  of the difference  $\Delta$  between the old and new value is determined by the relaxation time  $1/k_{10}$  (see also p. 142), where  $k_{10}$ , as defined in the previous section, gives the number of times

in unit time that a quantum  $h\nu$  of vibrational energy goes over into translational or rotational energy.  $1/k_{10}$  is therefore the life-time of the vibrational quantum. If we now allow an expansion to take place, the process takes place in the reverse direction, and a finite time is again required for the vibrational energy to die down. If a sound wave now goes through the gas, say a compression wave of square form for the sake of clearness, the total energy less the energy of vibration—that is to say, the sum of

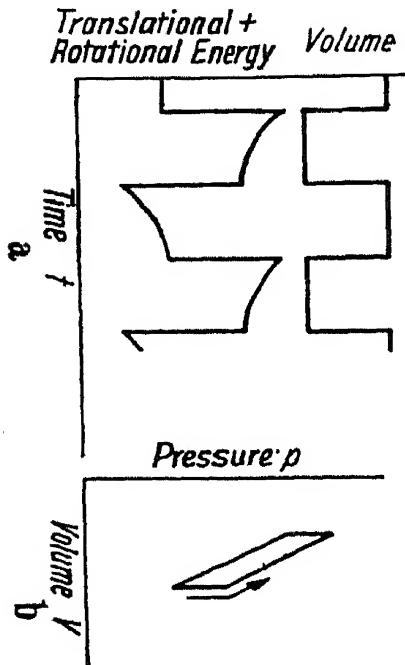
the translational and rotational energies—follows with time a course given by the lower curve of fig. 109 (a); this also represents the dependence upon pressure in the gas. The upper rectangular curve represents the simultaneous change in volume of the gas. We see immediately that the pressure and compression are not in phase; while, for example, after the first compression the volume immediately takes its final value and remains constant, the pressure continues to fall, since the energy of vibration is only set up gradually. If we form the  $p, V$  diagram from the two curves, we get the curve given in fig. 109 (b), which encloses a finite surface, outlined counter-clockwise. The thermodynamic meaning of this is that the mass of gas in question is continually doing work which is transformed irreversibly into heat and taken from the sound wave.

FIG. 109. Pressure and compression in a rectangular sound wave when equilibrium is incomplete (Kneser).

The absorption coefficients  $A'$  per wave-length (see the equation defining this on p. 129) is given according to Kneser (252, 254, 258) by the relation

$$A' = \frac{R c_{vi}}{\pi c_{va}(R + c_{vi})} \frac{k_{10} \cdot \omega}{k_{10}^2 + \omega^2},$$

the letters of which have the same sense as given on p. 139.  $A'$  is approximately equal to  $\pi \tan \phi$ , where  $\phi$  is the phase difference between the pressure and the density in the sound wave.  $\tan \phi$  is obtained by forming the product of the imaginary and real part of the velocity of sound, which is a complex quantity.



We further see that  $A'$  assumes a maximum value given by

$$A'_{\max} = \frac{\pi}{2} \frac{R c_{vi}}{c_{va}(R + c_{vi})}$$

at the angular frequency  $\omega_{\max} = 2\pi N_{\max} = k_{10}$ . Fig. 110 gives the absorption curve plotted against  $\log N$ ; the half-value region of the curve covers a frequency range of almost 4 octaves. The dotted curve represents the course of the sound dispersion as discussed earlier (see fig. 101). We may therefore say by way of summary that at low-sound frequencies the classical absorption is predominant, but over a certain range of frequency, different for every gas, the absorption rises on account of molecular processes, reaches a maximum value, and finally again approaches the classical value at higher frequencies.  $A'$  is independent of  $k_{10}$ , and may be easily calculated from thermal data. The excellent agreement between theory and experiment is shown by Table XVIII, which gives the measured and calculated values of  $A'_{\max}$  for air and oxygen at different temperatures and frequencies, according to Kneser and Knudsen (259).

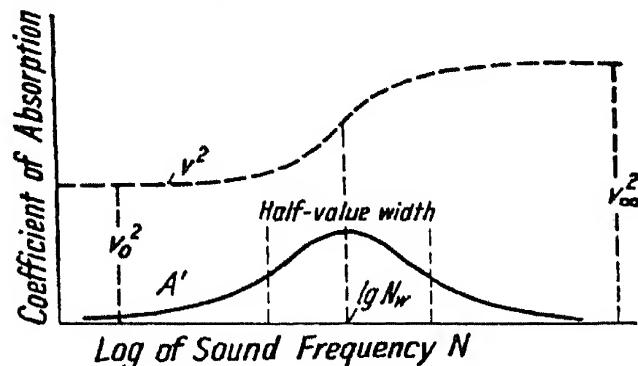


FIG. 110. Course of sound absorption and dispersion in a polyatomic gas.

TABLE XVIII

*Sound Absorption Coefficients in Air and Oxygen as Measured and Calculated for different Temperatures (Kneser and Knudsen)*

Gas	Temperature °C	Frequency kHz	$A'_{\max} \times 10^4$	
			Observed	Calculated
Air .	20	3	21.7 ± 2	21.8
	20	6	20.6 ± 1	21.8
	20	10	21.1 ± 1	21.8
	55	3	41.0 ± 6	39.4
	55	6	44.4 ± 4	39.4
	55	10	35.9 ± 4	39.4
Oxygen .	20	3	106.0 ± 10	104.0
	20	6	103 ± 10	104.0
	55	3	201 ± 20	188.0
	55	6	189 ± 19	188.0

It must further be pointed out that, as already discussed in the previous section,  $k_{10}$  and hence  $\omega_{\max}$  are not constants of the gas under investigation but increase with pressure and temperature, and are also greatly dependent upon admixture of foreign gases. The latter point renders very difficult the comparison of absorption measurements by different observers, since it is not always certain whether the gases investigated were fully free from impurities and especially water vapour. Fig. 111

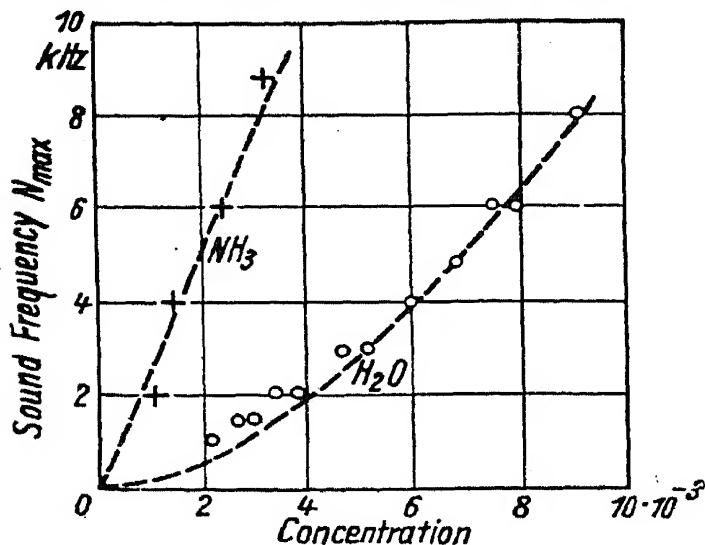


FIG. 111. Dependence of sound frequency at which the maximum absorption takes place upon amount of foreign gas in oxygen (Kneser).

$\text{CCl}_4$ ,  $\text{CO}$ ,  $\text{H}_2$ ,  $\text{CO}_2$ , and  $\text{He}$ . But in the case of  $\text{H}_2\text{O}$  the increase is considerably greater than proportionate.

The special position of water vapour as regards the effect of its presence on sound absorption is, in the case of air, also of practical importance in the applications of ultrasonics, for example, their use for signalling. The absorption of sound in air as dependent on the moisture content has been determined by Knudsen (262-266), Kneser and Knudsen (259), and Knudsen and Obert (267) by the echo method to be described below. The absorption measurements in air with various percentages of  $\text{CO}_2$ , as dependent on the degree of moisture, has been carried out by Rogers (394, 395). The absorption coefficient  $m = 2\alpha$  governing the decrease in intensity of sound in a plane wave is plotted in fig. 112 against the frequency  $N$  for different relative humidities at  $20^\circ \text{C}$ , and in fig. 113 for different temperatures with humidity 50 per cent. (Kneser, 258). We see that as the frequency rises the absorption increases

gives for oxygen the dependence of the frequency  $N_{\max}$  of maximum absorption, plotted against the concentration  $h$  of the foreign gas. Since  $N_{\max}$  is, from what has been said, equal to  $k_{10}/2\pi$ , we also get a general idea of the relaxation time  $1/k_{10}$  of the heat of vibration. It follows from fig. 111 that  $k_{10}$  increases proportionally to  $h$  when  $\text{NH}_3$  is the added gas, and the same is also true for the addition of  $\text{C}_2\text{H}_5\text{OH}$ ,  $\text{C}_2\text{H}_2$ ,  $\text{C}_6\text{H}_6$ ,  $\text{H}_2\text{S}$ ,

greatly with humidity and temperature. Fig. 113 gives also the course of the classical absorption  $m_{\text{class}}$ . It is only very slightly dependent on the temperature, and plays hardly any part as compared with the molecular absorption. We are so far without any clear explanation in detail of the strong influence of water vapour on the relaxation time of the heat of vibration, and hence of the dependence of maximum sound absorption on frequency. Perhaps we are here dealing with threefold collisions, so that when there is a collision between a vibrating oxygen molecule and two water molecules simul-

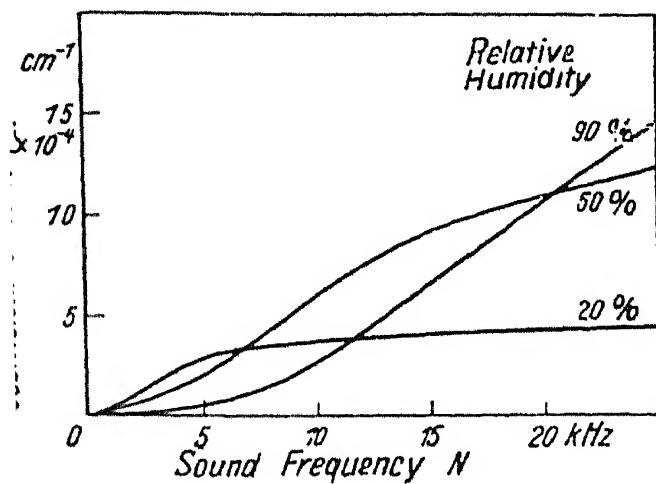


FIG. 112. Absorption coefficient per centimetre in air at  $20^{\circ}$  for different degrees of humidity (Kneser).

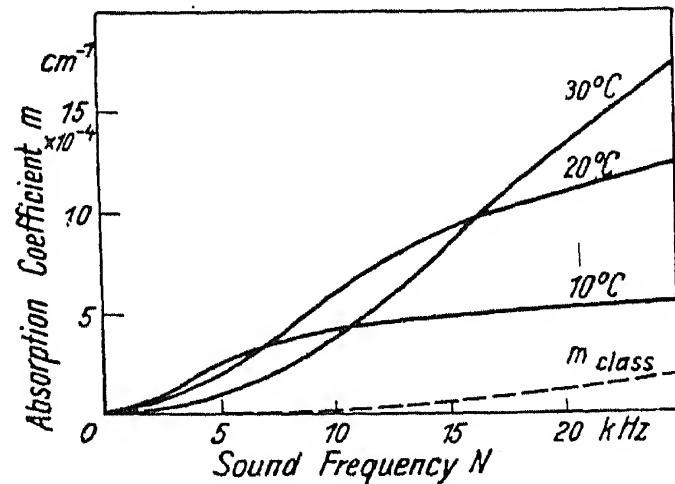


FIG. 113. Absorption coefficient per centimetre in air of 50 per cent. relative humidity at different temperatures (Kneser).

taneously, the heat of vibration is particularly easily transformed into translational or rotational energy. On the other hand, it is not impossible that a reaction  $\text{O}_2 + 2\text{H}_2\text{O} \rightleftharpoons 2\text{H}_2\text{O}_2$ , which is at any rate theoretically possible, may be responsible for the anomalous effect of water on sound absorption in air, from considerations given by Franck and Eucken, referred to on p. 145.

The measurement of sound absorption in gases has been carried out by various methods, some of which are very similar to those used for liquids. Abello (1, 2) measured the absorption of sound in  $\text{CO}_2$ ,  $\text{NO}_2$ ,  $\text{H}_2$ , and  $\text{He}$  mixed in various proportions with air, using, however, only a single frequency of 612 kHz. His method was to put between a piezoelectric source and a piezoelectric receiver tuned to it an absorption tube filled with the gas under investigation, and having its ends closed by windows of thin cellulose. This absorption vessel, which had in it a number of velvet baffles for avoiding disturbing reflections

from the walls, was made in two lengths, 10 and 3.5 cm. Celluloid filters of different thicknesses could be put in the path of the sound ray, and their transparency for sound determined by special experiment; they serve for calibrating the receiver. The valve voltmeter used as indicator on the receiver has already been described on p. 55.

Very extensive measurements of the sound absorption in  $\text{CO}_2$  in air at frequencies between 300 and 1400 kHz were carried out by Pielemeier (355-357, 360), using the Pierce ultrasonic interferometer, and determining the absorption constant by the magnitude of the reaction of the reflected sound wave of the quartz source. Pielemeier thereby assumes that when the reaction of the sound wave on the source is weak, the change in the deflection of the galvanometer in the anode circuit of the valve oscillator is proportional to the square of the alternating sound pressure on the quartz plate. This is not, however, necessarily always the case, as pointed out by Klein and Hershberger (249), for the reaction of the sound wave may also change the total decrement of the oscillating circuit by which the quartz is driven. This method, therefore, requires a special calibration of the apparatus, in order to be safe from error.

The change in the constants of the electrical oscillatory circuit caused by the sound reaction may be avoided in absorption measurements, according to Hubbard (223, 224) and Hershberger (198), by using electrical means to compensate the change in the apparent mechanical resistance produced by the sound absorption, in a way similar to that described on pp. 56 and 57 for the interferometer arrangement of Hubbard and Loomis for sound velocity measurements. This may be done, for example, by Hubbard's method (224) of cutting a capacity in or out of the oscillatory circuit, the value of this capacity for different distances of the reflector allowing the absorption coefficient of the gas investigated to be calculated. Hershberger (198) puts a variable resistance in parallel with the quartz source, adjusting it so that the voltage at the electrodes of the quartz source are the same for every position of the reflector. We have four values of the resistance,  $W_0$ ,  $W_1$ ,  $W_2$ , and  $W_3$ , for the four positions of the reflector,

$$l_0 = \left( n \pm \frac{\Lambda}{2} \right) \frac{\Lambda}{2}, \quad l_1 = n \frac{\Lambda}{2}, \quad l_2 = 2n \frac{\Lambda}{2} = n\Lambda, \quad \text{and} \quad l_3 = \left( 2n \pm \frac{\Lambda}{2} \right) \frac{\Lambda}{2},$$

and from these the absorption coefficient  $\alpha$  may be calculated by means of the equation

$$\alpha = \frac{1}{2l_1 \text{ Col}} \frac{(W_1 - W_0)W_2W_3}{2(W_2 - W_3)W_0W_1}.$$

Finally, Hubbard gives a full description (226) of a method of measuring the absorption coefficient, in which the vibrating quartz of the interferometer is not connected as usual parallel to the oscillatory valve circuit, but to the variable condenser of an intermediate circuit which may be tuned, and which is loosely coupled with the actual valve oscillator. The intermediate circuit contains a thermocouple connected to a galvanometer measuring the current taken by the vibrating quartz. This changes periodically with the displacement of the reflector, and both the absorption coefficient of the medium traversed by the sound, and also the absorption factor of the reflector may be measured by measuring the changes in current for different distances of the reflector. Curtis (119) used this method for determining the absorption coefficients of  $\text{CO}_2$ , air, and helium containing impurities.

In all methods so far described for measuring sound absorption, the sound wave is assumed to be plane, which, however, can never be completely realized in practice, as already pointed out on p. 114. It is particularly difficult at low-sound frequencies to build a source of sound of so great a diameter in relation to the wave-length, that the transmitted wave may be regarded as plane, at least in the neighbourhood of the source. In order to avoid this source of error, Grossmann (171) uses as a source the ends of longitudinally vibrating quartz rods, which he screens to such an extent that the emitted wave may be regarded as spherical. If we then measure the decrease in sound intensity with increase of distance between the sound source and receiver, the absorption coefficient in the gas investigated may be determined from the amount by which the decrease of sound intensity is in excess of  $1/r^2$ . Grossmann made measurements in air,  $\text{CO}_2$ , and  $\text{SO}_2$  by this method.

The most accurate method for measuring absorption has been developed by Knudsen (262, 264). It depends on the measurement of the echo time of the sound in a closed chamber,

the influence of the wall absorption being separated from that of the gas absorption by using chambers of different sizes. The absorption coefficient may be determined from the curves giving the rate at which the sound dies away, these curves being recorded very accurately by an automatic apparatus. This method has, however, so far only been used for audible frequencies up to 20 kHz, so that there is no need to go into it here in detail. Kneser and Knudsen (259) used it to measure the maximum absorption of sound in air and oxygen at different temperatures and frequencies between 3 and 10 kHz. The results have already been given in Table XVIII. The influence of foreign gases and of moisture of sound absorption in air and oxygen is also determined by this method (257).

## CHAPTER IV

# THE MEASUREMENT OF THE VELOCITY OF SOUND IN SOLIDS, AND THE DETERMINATION OF THE ELASTIC AND ELASTO-OPTICAL CONSTANTS

WHILE liquids and gases are able to carry only one sort of elastic waves, namely, compression waves—that is to say, pure longitudinal vibrations—in solid bodies, transverse and torsional vibrations may also be present, having as a consequence transverse waves. The reason for this lies in the fact that in solid bodies we may have not only pure compression and expansion, but also a shearing strain produced by shearing forces, which is not possible in liquids and gases owing to the absence of elasticity of shear. The velocities of propagation of the different elastic waves in solids are different, being determined by the elastic constants. The number of these constants in the simplest case, namely, that of an isotropic body, is two, while in the case of anisotropic bodies, crystals, it is dependent on the particular system of which the crystal belongs. In the most general case of the triclinic system we have twenty-one independent constants, in the regular system only three.

The elastic behaviour of the isotropic body may be completely described by the two Lamé elastic constants  $\delta$  and  $\mu$ .\*  $\mu$  is here identical with the modulus of torsion. For the velocity of propagation  $v_l$  of an elastic longitudinal wave in an infinitely large solid body, the theory of elasticity † gives us the expression

$$v_l = \sqrt{\frac{\delta + 2\mu}{\rho}} \quad (\rho = \text{density}), \text{ while for the velocity } v_t, \text{ purely trans-}$$

versal or shearing wave, it gives us the relation  $v_t = \sqrt{\frac{\mu}{\rho}}$ .

\* The Lamé elastic constants are usually denoted in the literature by  $\lambda$  and  $\mu$ . Since we are using  $\lambda$  in this book for the wave-length of light, we have chosen  $\delta$  in its place.

† See Lamb, *Dynamical Theory of Sound* (London, 1925), p. 120.

It has been found convenient to introduce two further elastic constants, namely, Young's modulus  $E$  and Poisson's ratio  $\sigma$ . We then have the equations

$$E = \frac{\mu(3\delta + 2\mu)}{\delta + \mu} \quad \text{and} \quad \sigma = \frac{\delta}{2(\delta + \mu)}.$$

The three magnitudes  $E$ ,  $\mu$ , and  $\sigma$  are naturally not independent of one another, but connected by the relation  $E/2\mu = 1 + \sigma$ . Using these constants we get

$$v_l = \sqrt{\frac{E}{\rho} \frac{1 - \sigma}{(1 + \sigma)(1 - 2\sigma)}} = \sqrt{\frac{E}{\rho} \frac{1}{\left(1 - \frac{2\mu^2}{1 - \mu}\right)}}; \quad v_t = \sqrt{\frac{E}{\rho} \frac{1}{2(1 + \sigma)}} = \sqrt{\frac{\mu}{\rho}}.$$

As already remarked, the foregoing expressions are valid for the velocity of the waves in question in a medium unlimited in extent; in the case of a long rod, the thickness of which is negligible

compared with its length, the equation for  $v_l$  reduces to  $v_l = \sqrt{\frac{E}{\rho}}$  for propagation of the longitudinal waves in the direction of the axis of the rod. The equation for  $v_t$  remains unaltered.

The measurement of the velocities  $v_l$  and  $v_t$  in an isotropic solid thus gives us a method for determining the elastic constant. The method best known is to excite longitudinal as well as torsional oscillations in long rods by means of friction, the frequency  $N$  being determined acoustically or by Kundt's method of dust figures, and to work out the elastic constants  $E$  and  $\mu$  from  $N$  and the elastic wave-length  $\Lambda$ , which for a rod of length  $l$  excited in the fundamental vibration is equal to  $2l$ . Here, however, a correction for the velocity of propagation  $v_l$  has to be made in the case of rods of finite section, this correction being first pointed out by Rayleigh (375), who took into account the influence of the increases and decreases of cross-section caused by the longitudinal compression and expansion. Taking this into account, we get the equation

$$v_l = \sqrt{\frac{E}{\rho} \frac{1}{(1 + \epsilon)^2}},$$

where  $\epsilon = \frac{\pi^2 \sigma^2 z^2 r^2}{4l^2}$  and  $\sigma$  is Poisson's ratio,  $r$  the radius of the rod,  $l$  the length of it, and  $z$  the number of elastic half wave-lengths in

the whole rod. As Boyle and Sproule (86, 87) were able to show experimentally in the case of duralumin rods vibrating longitudinally, and Giebe and Scheibe (165) in vibrating quartz rods, further departures from simple relations take place with the higher overtones, not accounted for by Rayleigh's corrections. They arise from coupling between the elastic longitudinal oscillation and the simultaneous radial expansion oscillations. Scheibe and Blechschmidt (163) gave an exact theory of these processes, and were able to find good confirmation of their theoretical results in measurements of the natural oscillations of nickel rods and tubes up to frequencies of 800 kHz.

The foregoing remarks show that in deriving the elastic constants from the natural frequencies of rods it is necessary to take precautions and apply corrections which make the method comparatively troublesome. In addition to the work already referred to, Muzzey (331) made investigations of ferromagnetic rods, which he set in longitudinal oscillation up to about 70 kHz by means of magnetostriction. Quimby (370), using rods of aluminium, copper and glass excited to elastic vibration by a piezocrystal cemented to one end, determined the velocity of sound in these materials, and also the coefficient  $\eta$  of internal friction, which is of the order of  $10^3$  ( $\text{cm}^{-1} \text{g sec}^{-1}$ ), and, according to Stokes (444, 445), lowers the velocity of sound in a manner given by the equation

$$v_i = \sqrt{\frac{E}{\rho} - \left( \frac{4}{3} (1 + \sigma) \frac{\eta}{\rho} \right)^2 \frac{k^2}{4}}$$

here  $k = \frac{2\pi}{\Lambda}$ . For  $\frac{\eta}{\rho}$  we get for aluminium the value  $0.54 \times 10^3$ , for copper  $2.8 \times 10^3$ , and for glass  $2.4 \times 10^3$ . Its influence on the velocity of sound is thus very small even at high frequencies, and practically negligible in most cases. The velocity of ultrasonic waves in cylindrical rods of steel, brass, copper, aluminium, and glass was recently investigated by Röhrich (393), using a range of frequencies up to 900 kHz; he also took into account the influence of the conductivity for heat on the propagation of sound. For this the introduction of an adiabatic modulus of elasticity  $E_{ad}$  is necessary, this being related to the statical modulus  $E_{is}$  by the following equation:  $E_{is}/E_{ad} = 1 - \frac{\alpha^2 T E_{is}}{\rho c_p}$ , where  $T$  is the absolute

temperature,  $\alpha$  the linear coefficient of expansion, and  $c_p$  the specific heat at constant pressure. The differences between  $E_{ad}$  and  $E_{is}$  are in all cases less than 0.5 per cent., and hence the influence of thermal conductivity on the propagation of sound is likewise negligible. Röhrich excited the metallic rods by means of a piezoquartz, which, however, was not cemented to the end of the rod, but vibrating in a vessel filled with oil, into which the end of the rod protruded. The oil transmits the high-frequency vibrations in sufficient intensity to the rod, which is held at the other end by a thread, and hence is able to vibrate in perfect freedom. The wave-length in the rod is made visible by dusting with lycopodium powder. Röhrich's experiments were continued by Schoeneck (424), who investigated in the same manner the elastic longitudinal vibrations of cylindrical single crystals at high ultrasonic frequencies. These investigations also showed in every case that the purely longitudinal expansion oscillations are disturbed by the simultaneous appearance of other waves (flexional and radial), and that Rayleigh's correction for thickness does not correctly represent the departures in the case of high frequencies. All these experiments were first interpreted correctly by the theory of Giebe and Blechschmidt already mentioned.

The correct determination of the elastic constants of a transparent body by means of ultrasonics may be carried out by using the diffraction of light by sound waves, according to a method given by Schaefer and Bergmann (410 to 415), which has the great advantage that all the elastic constants may be determined from one and the same sample of the substance under investigation, and that the values so obtained for anisotropic bodies represent a system of constants complete in itself, which was not the case in any previous method. At the end of Chapter II of this book (p. 101) we mentioned in the course of a discussion of optical diffraction by ultrasonics that the intersection of several sound waves produces a space grating of elastic waves, which gives rise to a complex diffraction image when illuminated with visible light. We then dealt only with the case of ultrasonic waves crossing one another in a liquid. It is an obvious step to transfer these considerations to a transparent solid. Let us take for the purpose a glass cube through which three ultrasonic waves are passing in three directions at right angles to the cube faces. This may be done, say, by cementing three like piezoquartz plates on

the cube faces and exciting them to elastic oscillation. If the frequency is rightly chosen, stationary waves are set up in the tubes, crossing one another at right angles. Experiments have shown that this rather troublesome method of producing the effect is happily unnecessary. It is sufficient to cement a quartz to only one side of the cube, or press it against the side with a thin film of oil between, or, still more simply, to lay the cube on a horizontal piezoquartz. Owing to the contraction in cross-section the cube is then set in strong oscillation in directions parallel to the surface of the quartz.

Since the piezoquartz (see p. 19) may be excited in almost any number of overtones, it is always possible to find one or more overtones of the quartz which throw the cube laid on it into very strong resonance vibrations. If a circular aperture is then made to form an image in the usual way through the vibrating cube on a screen, we get a very characteristic diffraction image, the form of which depends, in the case of isotropic bodies, only on the elastic constants of the vibrating body, and in the case of anisotropic bodies, also on the direction through which the light goes. The diffraction images are, however, completely independent of the external shape of the vibrating bodies. It makes no difference whether we use a cube, a rhombus, cylinder, or a prism. This fact is readily understood when we remember that the wave-length of sound responsible for diffraction is of the order of  $1/10$  to  $1/100$  mm, and so very small compared with the dimensions of the vibrating body. Hence the boundary conditions may be neglected, and the body regarded as infinite. Fig. 114 gives the diffraction image obtained when a vibrating cube of glass is illuminated with monochromatic light. It consists of two concentric circles, formed out of individual sharp interference points.

Fues and Ludloff (159) have given a theory for this diffraction phenomenon in vibrating transparent solids (see p. 173), according to which the inner circle is formed by diffraction of the light by an elastic space grating, generated by the longitudinal waves, while

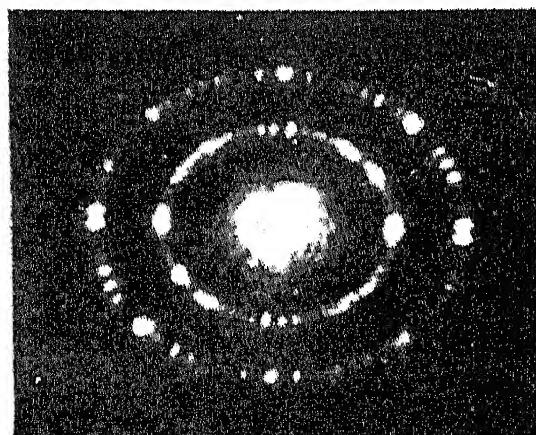


FIG. 114. Optical diffraction image formed by a vibrating glass cube (Schaefer and Bergmann).

the outer circle is to be ascribed to a grating of transverse or shear waves. We have thus two sorts of space gratings interlocked in the vibrating glass cube; they have different grating constants which in both cases will be given by the elastic wave-lengths. If we denote these by  $\Lambda_t$  and  $\Lambda_l$ , the distance of the diffracting cube from the image plane by  $A$ , and the wave-length of the light by  $\lambda$ , the radii of the two diffraction circles are given by the ordinary diffraction formula as

$$r_l = \frac{A\lambda}{\Lambda_l} \quad \text{and} \quad r_t = \frac{A\lambda}{\Lambda_t} (r_t > r_l).$$

If the frequency of the elastic oscillations is  $N$ , we get for the velocities of the two sound waves the equations

$$v_l = N\Lambda_l = \frac{NA\lambda}{r_l}; \quad v_t = N\Lambda_t = \frac{NA\lambda}{r_t},$$

or after introducing the elastic constants

$$\sqrt{\frac{\delta + 2\mu}{\rho}} = \frac{NA\lambda}{r_l}; \quad \sqrt{\frac{\mu}{\rho}} = \frac{NA\lambda}{r_t}.$$

From this we may calculate  $\delta$  and  $\mu$ , and also Poisson's ratio  $\sigma$ . A simple transformation of the equations gives us

$$\mu = \frac{N^2 \lambda^2 A^2 \rho}{r_t^2}; \quad \delta = N^2 A^2 \lambda^2 \rho \left( \frac{1}{r_l^2} - \frac{2}{r_t^2} \right); \quad \sigma = \frac{1 - 2(r_l/r_t)^2}{2 - 2(r_l/r_t)^2}.$$

Since all values on the right-hand side of these equations are known, it is possible to determine all the elastic constants of an isotropic body from a single photograph of the diffraction image. Before considering these measurements in detail a word must be said about the fact that a transverse wave produces a diffraction effect when ordinary light is used. According to what we said earlier on, light waves can only be diffracted by elastic waves when regions of compression and expansion occur at regular intervals—that is to say, the index of refraction of the medium changes from point to point periodically. This is the case in a pure longitudinal wave, while, on the other hand, a transverse or shear wave produces only shear. In the upper line of fig. 115 we have a number of volume elements of the isotropic body, which are adjacent to one another and taken for simplicity as having a

square section. If now a transverse wave runs along this row of elements, we have at a given moment the conditions represented by the lower row of figures. At the points of maximum amplitude of vibration the elements originally square are distorted into rhombs of the same area, the axes of which,  $\xi$  and  $\eta$ , are inclined at nearly  $45^\circ$  to the horizontal. In the  $\xi$  axis we have maximum compression and at the same moment in the  $\eta$  axis maximum expansion, or conversely, according as we are dealing with a wave crest as in 1 and 5, or with a wave trough as in 3 and 7. At the nodes 2, 4, and 6 the surfaces are undistorted. Two successive rhombs distorted alike, for example 1 and 5, are a

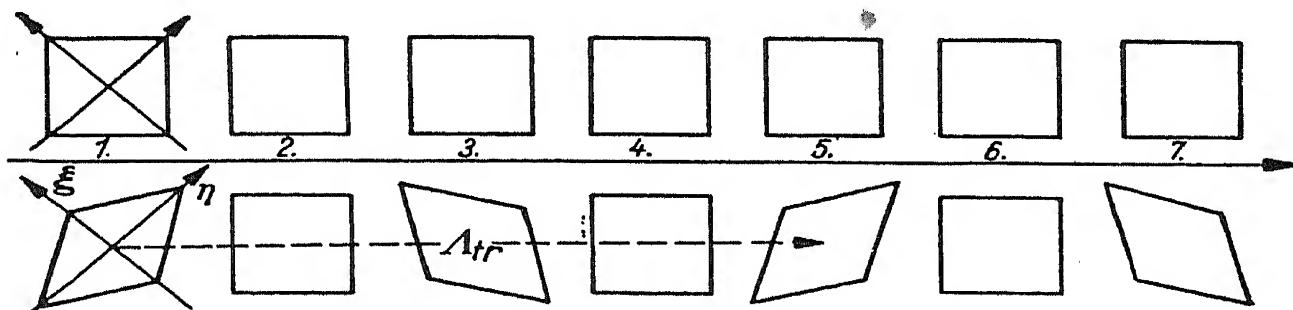


FIG. 115. Distortion produced by a transverse wave in a solid body at a given moment.

wave-length  $\Lambda_t$  apart. If we first consider the case of light polarized in one of the directions  $\xi$  or  $\eta$ , we then have obviously, exactly as in the case of a longitudinal sound wave, an index of refraction with the period of  $\Lambda_t$ , since the linear density changes periodically with  $\Lambda_t$ . We get the normal diffraction phenomenon—that is to say, we have in the direction of the elastic wave, to right and left of the central image, spectra the light of which retains its original condition of polarization. If the emergent light is sent through a second crossed Nicol, the diffraction image disappears. If we now take the second case, namely, when unpolarized light enters the transverse wave, we may resolve each light vibration into its  $\xi$  and  $\eta$  components. Each component gives us, according to the first case, a diffraction phenomena, and the two diffraction images coincide exactly, so we get a diffraction spectrum with unpolarized light. The case still to be examined, that of light polarized in any plane, is somewhat more complicated but leads to the same result, that a diffraction phenomenon takes place. This case is dealt with at length in a paper by Schaefer, Bergmann, and Goehlich (417).

The photographs reproduced in fig. 116 (see also ref. 414) give us a general view of the relations just discussed. All photographs were made with a cube of glass excited elastically from below. Fig. 116 (a) was made with unpolarized light ; we see that the inner circle, produced by the longitudinal wave, comes out considerably brighter. Fig. 116 (b) is made with light polarized

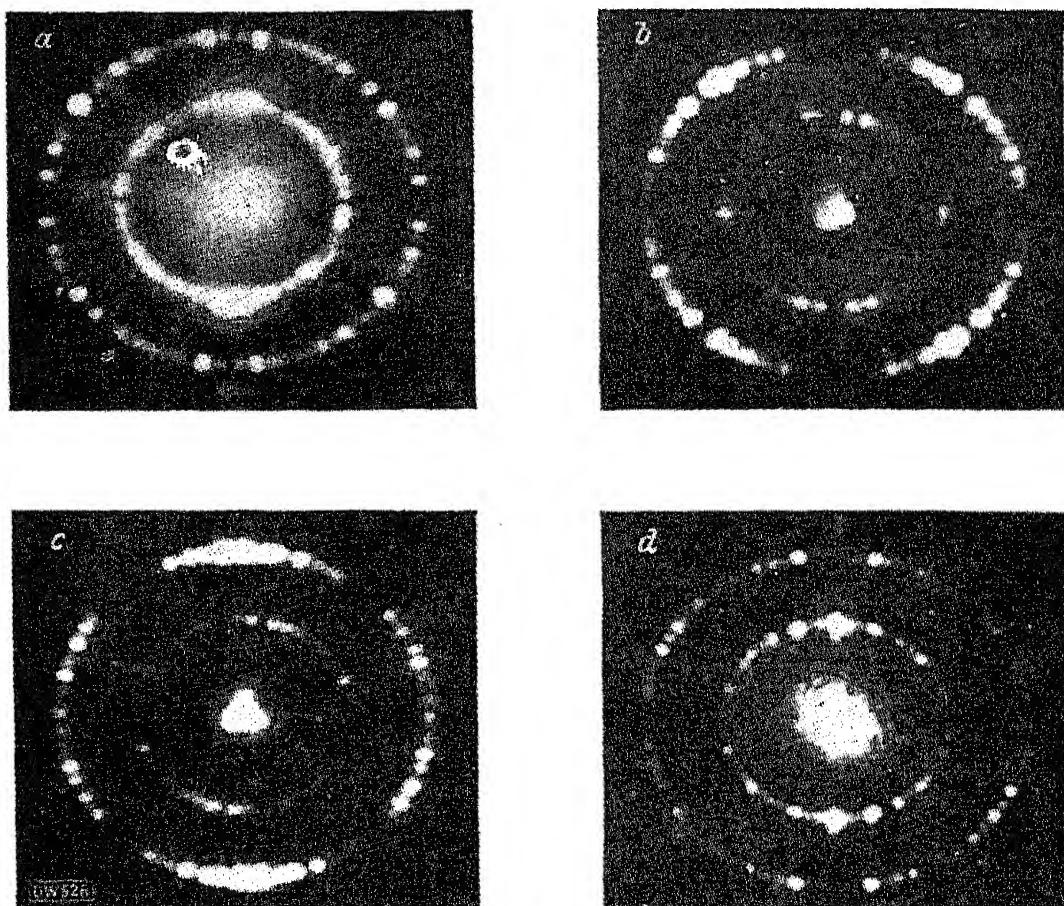


FIG. 116. Optical diffraction images of a vibrating cube of glass, (a) in unpolarized light, (b) and (c) between crossed Nicols, (d) in elliptically polarized light (Schaefer, Bergmann, and Goehlich).

at  $45^\circ$  and then observed through a crossed analyzing Nicol. The effect of this is, in the first place, to get rid almost completely of the inner circle, while in the outer circle we have the diffraction image extinguished in the horizontal and vertical direction. But the extinguished diffraction points belong to the transverse waves, the  $\xi$  and  $\eta$  axes of which fall in the direction of polarization of the entrant light. Fig. 116 (c) is also taken between crossed Nicols ; the direction of polarization of the entrant light is vertical. This results in the extinction of the diffraction point lying at  $45^\circ$  on the outer circle.

In order, therefore, to get diffraction by transverse waves,

it is by no means necessary to work with the crossed Nicol; but it is very convenient to do this for practical reasons, since the bright central image and the inner circle, which are easily over-exposed on account of their high intensity, may be in part extinguished. If elliptically polarized light is used, the intensity of the two circles may be got approximately equal. This is, for example, the case in fig. 116 (*d*), which also shows how very sharp the separate diffraction points on the interference curves may be got by using a sufficiently small aperture. Otherwise the ratio of the brightness of the two circles in glasses depends upon the elasto-optical constants (see p. 187).

This method was used by Schaefer, Bergmann, and Goehlich (417) in making systematic determinations of the elastic constants of seventy varieties of Schott's optical glass. The accuracy of measurement of  $\sigma$  and  $E$  is about 1 per cent., and of  $\mu$  about 0.8 per cent. This degree of accuracy, which at first sight seems rather low, does not depend upon the actual method, which gives considerably better results, but upon the phenomenon that the diffraction figures produced by the glasses show slight departures from circular form, which are caused, as far as our present experience goes, by small degrees of inhomogeneity or strains in the glass used. Investigations are in progress into the dependence of the electric constants of the glass on temperature and internal strain.

Fig. 117 shows a portable apparatus for optical diffraction experiments on vibrating solids. A glow-lamp (6V, 5A) in the lamp-house *B* (right front) illuminates through a condenser a small circular aperture, which is projected as a reduced image through a total reflection prism by means of the micro-objective *M*. This reduced image of the aperture (diameter about 1/100 mm) serves as the actual source of light and is focussed by the objective *O* sharply on the plate of the camera *K*. In front of this objective we have the glass cube *G* under investigation, lying on a horizontal vibrating quartz. In order to get the distance between the glass tube and the photographic plate as great as possible but the apparatus sufficiently compact, the rays sent to the camera are bent twice by two right-angled prisms *P*. The diffraction image is first focussed subjectively by pushing in the eye-piece *C*, and then photographed by the camera *K*. Two polarization filters *F*<sub>1</sub> and *F*<sub>2</sub> allow of working

also by polarized light. The whole arrangement is fixed on a strong iron base plate.

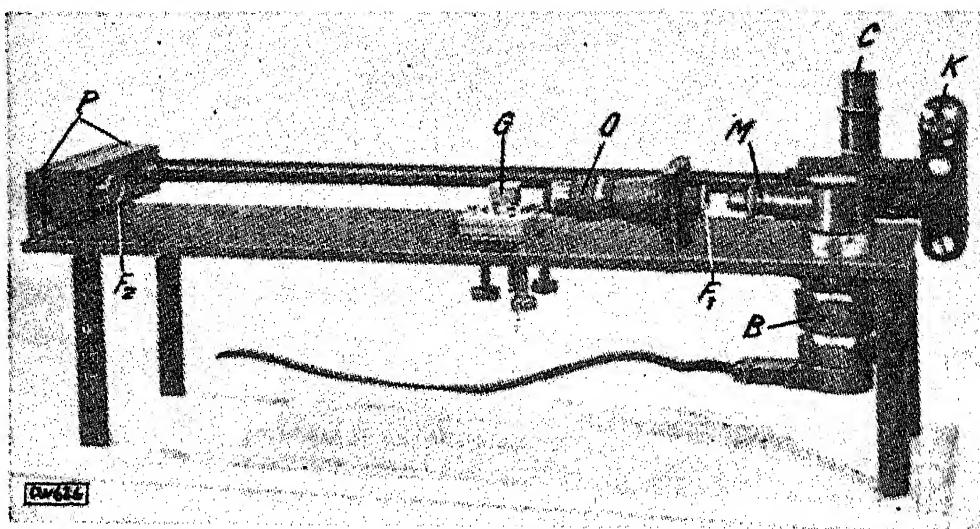


FIG. 117. Apparatus for optical determination of the elastic constants of glasses and crystals by the method of Schaefer and Bergmann.

We will now consider the diffraction phenomena exhibited by vibrating anisotropic bodies. The upper series of photographs of fig. 118 are diffraction images obtained by sending light

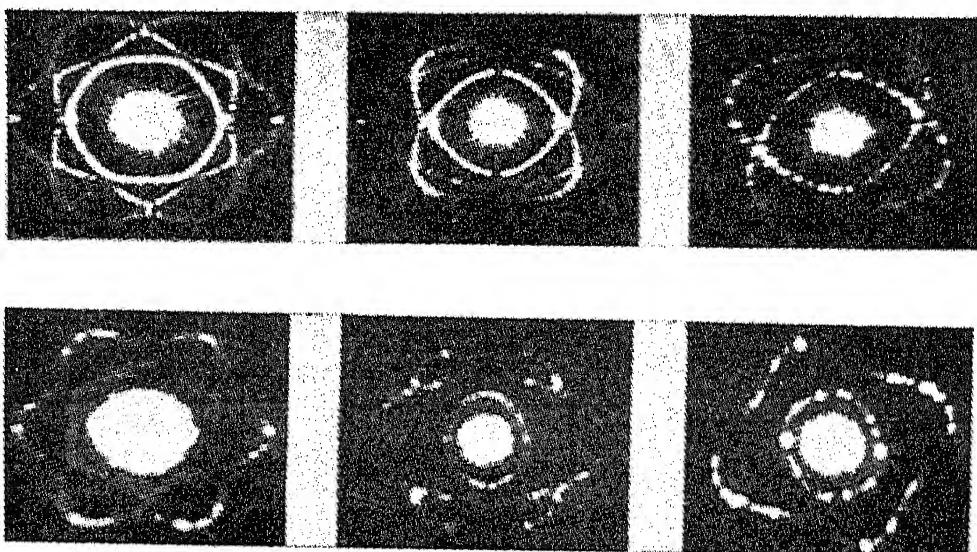


FIG. 118. Diffraction images formed by sending light through a vibrating quartz cube in the  $ZY$  and  $X$  axis (upper series) and a calcspar cube in analogous directions (lower series) (Schaefer and Bergmann).

through a tube of quartz vibrating ultrasonically in three directions at right angles to one another— $Z$  the optical axis,  $Y$  and  $X$  the electric axes. We see at once that the interference images, which in some cases are very complex, represent the elastic

symmetry of the crystals; thus we have round the optic axis a sixfold effect, round the  $Y$  and  $X$  axes a twofold effect. A further striking point is the oblique figure given by the light passing through the  $X$  axis; its position is likewise given accurately by the elastic relations of the quartz. The angle of inclination to the horizontal  $Y$  axis is  $18^\circ$ , and coincides with the direction of the smallest elastic modulus, as we see at once by comparison with fig. 21, where the direction is that of  $72^\circ$ .

The second row of photographs in fig. 118 give the analogous images produced by a vibrating cube of calc spar, which belongs to the same crystalline system. We recognize at once their great similarity with the

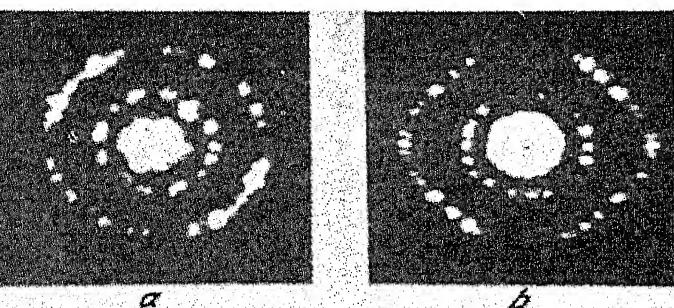


FIG. 119. Diffraction images formed by sending light through a beryl crystal (a) in direction of the optical axis, (b) at right angles to the same (Schaefer and Bergmann).

figures obtained by sending light through the quartz in the  $Z$  and  $Y$  axes respectfully, and we again find in the case of the  $X$  axis an oblique interference image with twofold symmetry. Fig. 119 gives results for beryl with light sent through the optical axis (a), and in a direction at right angles to it (b); figs. 10 to 12 of fig. 121 give the diffraction images for barytes, a member of the rhombic system, for the two chief axes at right angles to one another. Finally, we have in fig. 120 four crystals of the regular system: fluor spar, rock salt, sylvine, and lithium fluoride,

Fluor Spar

Rock Salt

Sylvine

Lithium Fluoride

FIG. 120. Diffraction images formed by sending light through regular crystals in a direction at right angles to a cube face (Schaefer and Bergmann).

lithium fluoride; these were obtained by setting up the crystals in equivalent directions, and sending light through in a direction at right angles to a face of the cube. They show the fourfold symmetry very clearly. But if a regular crystal is illuminated

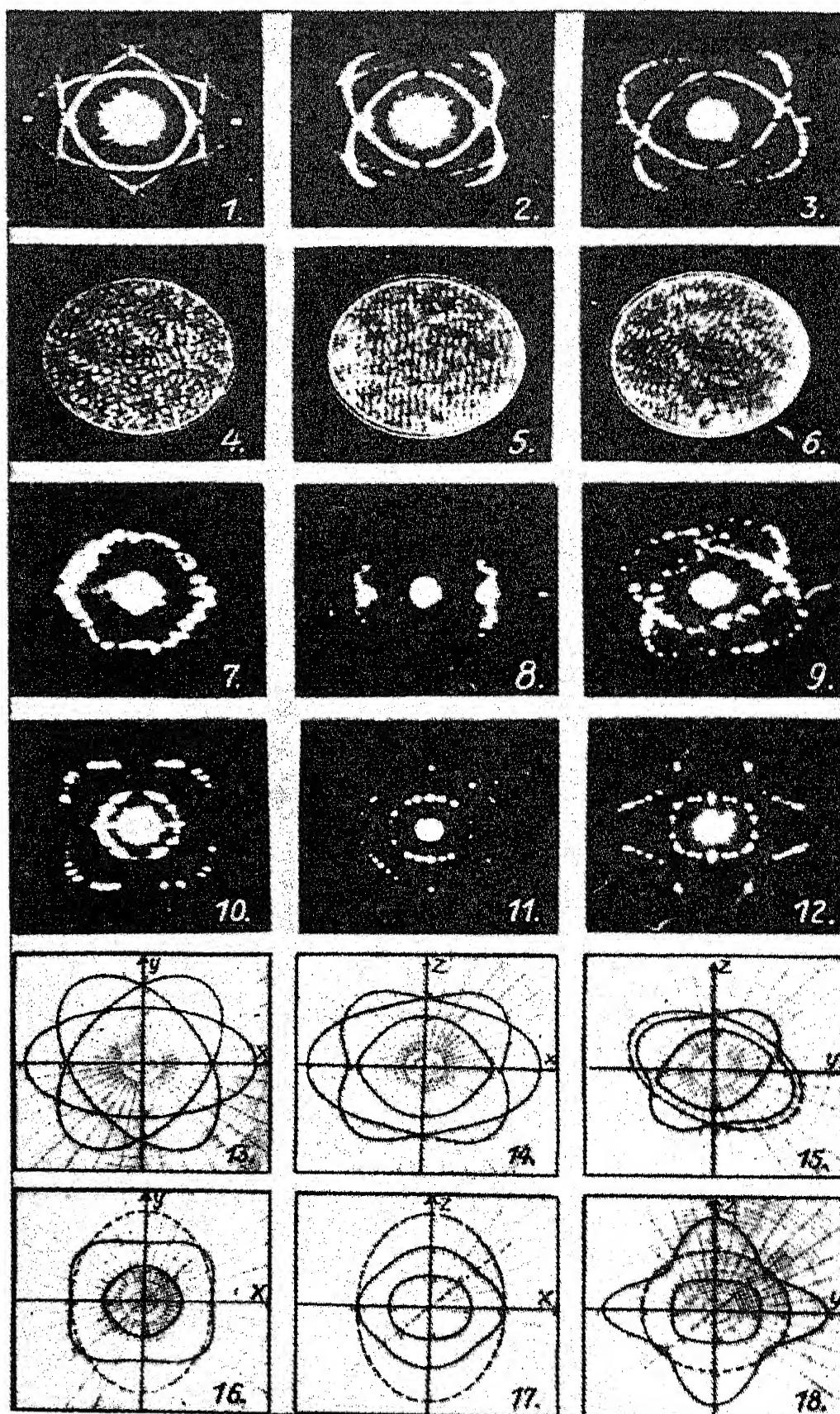


FIG. 121. Optical diffraction images produced by vibrating crystals (Schaefer and Bergmann). 1 to 3, experimental result with quartz; 4 to 6, sections of gratings; 7 to 9, secondary diffraction images; 10 to 12, barytes experimentally; 13 to 15, quartz theoretically; 16 to 18, barytes theoretically.

he direction of a diagonal of the cube, we get, as we should expect, threefold symmetry such as is shown for fluor spar in 122. The greater part of these diffraction images obtained in crystals show special phenomena in polarized light, some which consist in the extinction of certain parts of the interference images, according to the position of the direction of vibration of the incident light. These phenomena are, however, complicated that nothing further is to be said at present but their cause, and we will content ourselves here with referring to what has been published on the subject up to the present (411, 413).

How are these diffraction images to be explained according to the theory of Fues and Blooff (159) ? The supposition which was first put forward, that we are dealing with analogous optical diffraction effects to those

which in the case of X-rays acting on crystals, is not completely true. In the first place, the diagrams here obtained consist entirely of curves running round the central point, whereas the Laue diagrams consist of branches of parabolas and hyperbolas running through the central point. The optical diffraction phenomenon is only selective in a very small degree; that is to say, it is not necessary to use a wide range of the spectrum—in other words, white light—for producing it, as is necessary in the case of the Laue diagram; to the contrary, it is obtained with strictly monochromatic light. The optical diffraction images always contain only spectra of first order; this is to be explained by the sine law distribution of intensity in the diffracting sound waves, the intensity of which is comparatively small. But a limitation to diffraction images of the first order would give, in the case of Laue diagrams, only a very few, in general only four, diffraction points, which, according to Laue's theory, result from the rare meeting of the interference cones at the photographic plate. The optical diffraction images, on the other hand, are composed of a large number of interference points very close together. This is only

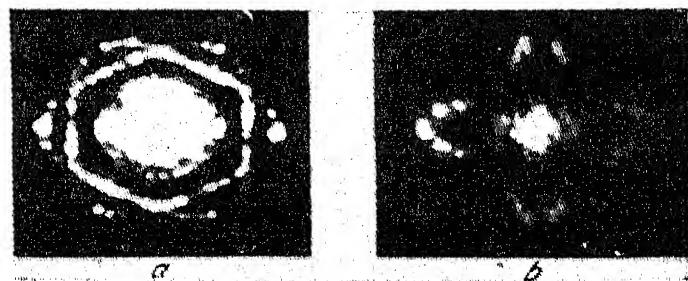


FIG. 122. Diffraction image formed by a fluor spar crystal in the direction of a diagonal of the cube, and by a zircon crystal (tetragonal) parallel to the optical axis (Schaefer and Bergmann).

to be explained by the assumption that the vibrating body contains a large number of three-dimensional space gratings, of which each produces only a small number of interference points. Schaefer and Bergmann (415) were able to prove this experimentally in two different ways. If the exciting frequency is thrown somewhat out of tune, we frequently get the case of nothing being left of the whole interference figure but four diffraction points, which must therefore come from one single three-dimensional space grating, and which, when the distuning is carried further, suddenly appear on the interference image at another point, this being due to a different grating being excited. Schaefer and Bergmann name this wandering of the interference point produced by slight distuning of the oscillator 'scintillization' (*Szintillisieren*). These two authors further succeeded in photographing a section through the elastic grating present in the vibrating crystal, using the striation method described on p. 58. We reproduce photographs of this sort for sections at right angles to the  $Z$ ,  $Y$ , and  $X$  axis in the case of quartz in figures 4 to 6 of fig. 121. We see how extremely complicated the grating is, and that we are therefore not dealing with a simple space grating. In order to demonstrate the reality of these sections of gratings, Schaefer and Bergmann used these photographs of grating sections as a diffracting system. The secondary diffraction images, given in photographs 7 to 9 of fig. 121, do in fact show the elastic symmetry of the quartz present in the direction in question. Fues and Ludloff therefore assume as an explanation of the numerous individual gratings in the vibrating crystal, that all elastic natural frequencies of the body are available, which are in more or less good resonance with the exciting frequency. Since the resonance curve of the quartz exciting the vibrations had a finite breadth, the number of natural frequencies which may be excited is of the order of 100. Now we have already pointed out that the boundary conditions of the vibrating body have no influence on the form of the interference curve, so that the body may be taken as of infinite size. We may therefore take as natural frequencies all plane waves which pass through the crystal in any direction. If we consider for all directions those plane waves belonging to a certain frequency, their wave-lengths will by no means be in every case the same in a polar diagram, but will represent, in

heir dependence upon direction, the symmetry and elastic elations of the crystal. Only in the case of isotropic bodies shall we get for the phase surfaces of all these waves spheres, while for crystal systems we shall get surfaces of a higher order. Our first task is to find the relation between the exciting frequency and the elastic wave-lengths or the propagation vector of the waves in a certain direction; this relation, since it gives the connection between frequency and the form of vibration suited to the crystal symmetry, is given the name 'form-frequency' relation. This problem is solved by setting up for the system typical of each class of crystals three differential equations of vibration, which may be deduced from the elastic potential of the medium in question.\* If this system of equations is integrated on the assumption of a plane wave, the solution gives us an equation of the sixth degree, containing, besides the exciting frequency, only the propagation vector  $\mathbf{k}$  of the wave, and the elastic constants of the body. The equation represents a surface of the sixth order, which we will term the 'form-frequency surface.' This may be pictured geometrically by imagining

the propagation vector  $\mathbf{k} = \frac{2\pi}{\Lambda} \mathbf{n}$  plotted in each direction in space;

here  $\mathbf{n}$  is the unit vector in the direction of the normal to the wave. The point of the vector  $\mathbf{k}$  then lies on the aforementioned form-frequency surface, which in general consists of three layers, since according to the theory of elasticity three waves belong to each direction of propagation. The distortion vectors of every three associated waves are at right angles to one another in pairs, so that they form together a rectangular system of co-ordinates. The special case, which we have with a body which is elastically isotropic, is that in which one of the distortion vectors coincides with the direction of the propagation of the elastic waves, one wave being therefore a pure compression wave; the other two waves belonging to the same direction of propagation must then be two pure transverse waves at right angles to one another.

It now only remains to find the connection between the form-frequency surface and the optical interference curve—that is to say, we have to find the conditions telling us which elastic waves

\* See, for example, Schaefer, *Einf. i. d. theor. Physik*, vol. i, 3rd ed., pp. 512 and 535 (Berlin, 1929); Love, *Mathematical Theory of Elasticity* 3rd ed., Cambridge, 1920), p. 302 ff.

make a contribution to the interference phenomenon. In the following discussion only the experimental fact is of importance, that the angles of diffraction for the diffraction images of the first order are very small ( $\approx 10^{-2}$ ) and are given by the relation between the optical wave-length  $\lambda$  and the sound wave-length  $\Lambda$ . The theory of Raman and Nagendra Nath on the diffraction of light by sound waves, referred to on p. 77, tells us namely that diffraction of sensible intensity only takes place when the light traverses the sound wave in a direction approximately parallel

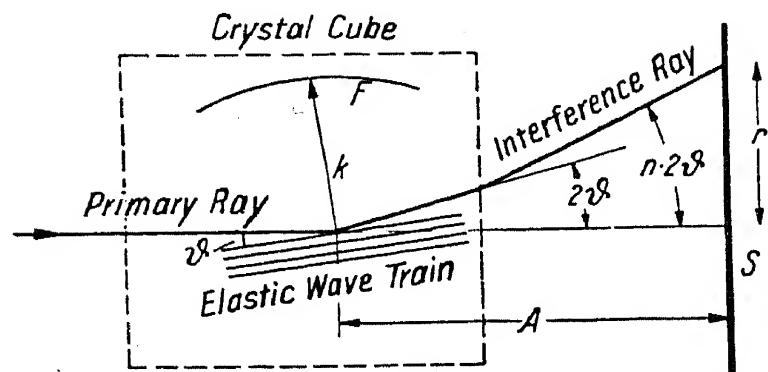


FIG. 123. Illustrating the production of interference figures in the diffraction images of Schaefer and Bergmann.

to its wave front. Hence in the present case the diffraction figure is produced essentially only by the contribution of those waves which carry out a longitudinal vibration at right angles to the direction of illumination, which therefore have a propagation vector ap-

proximately at right angles to the direction of the light. For the light diffracted by them, Bragg's relation must be formally true:  $2\Lambda \sin \theta = \lambda_i$ , where  $\Lambda$  is the elastic wave-length,  $\lambda_i$  the wave-length of the light in the interior of the crystal, and  $\theta$  the grazing angle at which Bragg reflection takes place. When the direction of the crystal with reference to the light and the wave-length of the latter are given, the Bragg relation gives us a one-dimensional manifold of plane waves. Fig. 123 gives one selective elastic wave at which diffraction as just described takes place. The plane of the paper is that of the primary incident ray, and the propagation vector  $\mathbf{k}$ . The point of the arrow on  $\mathbf{k}$  lies, as shown above, on the form-frequency surface  $F$ . The interference ray generated by this wave runs through the crystal at an angle  $2\theta$ , which on the ray leaving the crystal is multiplied by  $n$ . The ray reaches a screen  $S$  at a distance  $A$  displaced  $r$  from the primary spot; when the angle of diffraction is small,  $r$  is given with sufficient accuracy by  $r = An \times 2\theta$ . Combining this with the Bragg formula given above, we get

$$r = An \lambda_i \frac{1}{\Lambda} = A \lambda_a \frac{1}{\Lambda} = A \lambda_a \frac{k}{2\pi},$$

When we remember that  $\Lambda = \frac{2\pi}{k}$ , and that  $n = \frac{\lambda_a}{\lambda_i}$ . Fig. 123 shows that the interference figure is very approximately a geometrically similar image of the section through the form-frequency surface in a direction at right angles to the primary ray, but magnified in the ratio  $A\lambda_a/2\pi$ . In order, therefore, to deduce the interference curves theoretically, it is sufficient to find the intersection of the above equation of this surface with the plane at right angles to the direction of illumination. We then get in general a curve of the sixth order.

Fig. 121, 13 to 18, gives the interference figures for quartz and barytes calculated in this way. We recognize at once the complete agreement between these calculated curves and the experimental interference figures of photographs 1 to 3 and 10 to 12. Now and then the curves of the sixth order fall into a curve of the fourth order and an ellipse or circle as the case may be, as when the quartz is illuminated along the  $X$  axis, and barytes in any direction. The theory further tells us that these ellipses are produced by pure transverse waves, which in this case give no optical diffraction, since the distortion takes place in the same direction as that of the light. These ellipses are shown dotted in figures 13 to 18 of fig. 121. The conditions are simplest in isotropic bodies. The theory gives for these (cf. p. 175) two circles of different diameter as interference figures, the outer being two-fold and produced by the transverse wave. The doubling of the outer circle arises from two transverse waves with the same velocity of propagation, and giving a distortion component at right angles to the direction of illumination, so that a diffraction effect is produced according to the considerations given on p. 167.

The theory of Fues and Ludloff, therefore, now makes it possible to determine the elastic constants of crystals in a very simple manner. For this purpose it is generally sufficient to measure up the intercepts of the interference figures on the co-ordinate axes, and on a straight line through the middle point, inclined at  $45^\circ$  to the axes. We will denote for all three directions of illumination the points of interception of the interference curves on both sides of the middle point, counting from it outwards by  $a$  and  $b$  on the horizontal axis, by  $c$  and  $d$  on the vertical axis, and by  $e$  and  $f$  on the straight lines inclined at  $45^\circ$  (cf. 13 to 18 in fig. 121, in which, however, these letters are not given on account of the

smallness of the figures). We then have, for example, in the case of a crystal of the rhombic system the following set of equations for calculating the nine elastic constants  $c_{ik}$  :—

Observation parallel to the  $X$  axis.

$$(aa) \sim \frac{1}{\sqrt{c_{22}}} ; \quad (bb) \sim \frac{1}{\sqrt{c_{44}}}$$

$$(cc) \sim \frac{1}{\sqrt{c_{33}}} ; \quad (dd) \sim \frac{1}{\sqrt{c_{44}}}$$

$$\frac{(ff)^2 - (ee)^2}{(ff)^2 + (ee)^2} \sim \frac{\sqrt{(c_{22} - c_{33})^2 + 4(c_{23} + c_{44})^2}}{c_{22} + c_{33} + 2c_{44}}.$$

Observation parallel to the  $Y$  axis.

$$(aa) \sim \frac{1}{\sqrt{c_{11}}} ; \quad (bb) \sim \frac{1}{\sqrt{c_{55}}}$$

$$(cc) \sim \frac{1}{\sqrt{c_{33}}} ; \quad (dd) \sim \frac{1}{\sqrt{c_{55}}}$$

$$\frac{(ff)^2 - (ee)^2}{(ff)^2 + (ee)^2} \sim \frac{\sqrt{(c_{11} - c_{33})^2 + 4(c_{13} + c_{55})^2}}{c_{11} + c_{33} + 2c_{55}}.$$

Observation parallel to the  $Z$  axis.

$$(aa) \sim \frac{1}{\sqrt{c_{11}}} ; \quad (bb) \sim \frac{1}{\sqrt{c_{66}}}$$

$$(cc) \sim \frac{1}{\sqrt{c_{22}}} ; \quad (dd) \sim \frac{1}{\sqrt{c_{66}}}$$

$$\frac{(ff)^2 - (ee)^2}{(ff)^2 + (ee)^2} \sim \frac{\sqrt{(c_{11} - c_{22})^2 + 4(c_{12} + c_{66})^2}}{c_{11} + c_{22} + 2c_{66}}.$$

The proportionality factor appearing in the equation contains only known magnitudes, these being the frequency  $N$  with which the crystal is elastically excited, the apparatus constant  $A$  = distance of crystal from plane of picture, and  $\lambda$  = wave-length of the light used.

The constants with like indices follow directly from the intercepts on the axes, while the intercepts on the line inclined at  $45^\circ$  give an aggregate of the coefficients with unlike indices,

till unknown, and those already known. Similar equations may be set up for each system of crystals. Table XIX is a collection of constants measured by interference curves for barytes, and of the values measured statically by Voigt (465).  $c_{11}$  is assumed to be the same in the two cases for determination of the apparatus constants.

TABLE XIX

*Comparison of Elastic Constants determined from Interference Curves for Barytes with Values measured by Voigt*

$c_{ik}$	Measured from Interference Curves	Measured by Voigt
$c_{11}$	$9.0 \times 10^6$	$9.0 \times 10^6$
$c_{22}$	7.96	8.0
$c_{33}$	10.58	10.7
$c_{44}$	1.19	1.2
$c_{55}$	2.85	2.9
$c_{66}$	2.60	2.8
$c_{12}$	4.86	4.6
$c_{13}$	2.74	2.7
$c_{23}$	2.95	2.7

We see that the agreement is a very good one. When we consider that the constants determined by the optical method were derived only from three interference images obtained from the same crystal, whereas Voigt's constants depend on no less than 15,000 individual measurements made on several samples of the crystal, we get a clear picture of the possibilities of the new method. Table XX (p. 180) gives us the constants calculated for the three representatives of the regular system, the interference figures of which are shown in fig. 120.

The optical method with ultrasonic vibration naturally gives only the adiabatic elastic constants; generally speaking, however, these only differ very slightly from the isothermal constants measured statically (see p. 163).

A disadvantage of the optical method is, however, its limitation to transparent substances. But Schaefer and Bergmann (48, 416) have recently found a way of investigating the elastic properties of opaque crystals and glasses, as well as of metals. Since it is clear that the surface of a cube set in high-frequency vibration

TABLE XX

*Elastic Constants of Regular Crystals determined from Interference Curves, as compared with Measurements of Voigt*

Crystal	$c_{ik}$	Measured from Interference Curves	Measured by Voigt
Fluor spar . .	$c_{11}$	$16.76 \times 10^6$	$16.7 \times 10^6$
	$c_{44}$	3.69	3.46
	$c_{12}$	4.72	4.77
Rock salt . .	$c_{11}$	$4.77 \times 10^6$	$4.76 \times 10^6$
	$c_{44}$	1.21	1.29
	$c_{12}$	1.25	1.32
Lithium fluoride . .	$c_{11}$	$12.00 \times 10^6$	...
	$c_{44}$	6.4	...
	$c_{12}$	4.41	...

cannot remain plane, the experimental arrangement is altered to that shown in fig. 124. A circular diaphragm  $B$  is strongly illuminated by the source of light  $L$  through the condenser  $K$ , and an image is formed of it by the objective  $O$  on the photo-

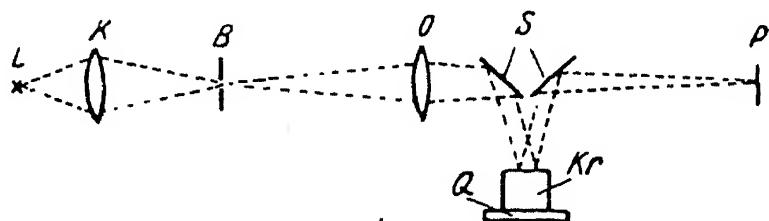


FIG. 124. Experimental arrangement for producing diffraction images by reflection of light from the surface of vibrating bodies.

graphic plate  $P$ . On its way from the objective  $O$  to the plate  $P$ , the light is reflected, by the aid of the pair of mirrors  $S$ , from the silvered surface of the crystal  $Kr$ , which is again set in high-frequency vibration in the ordinary way by means of a piezoquartz  $Q$ . Using monochromatic light, we then get diffraction images, which are likewise dependent on the elastic data of the vibrating body, but, on the other hand, not in any way influenced by the external form or boundaries of the reflecting body, so long as its dimensions are not of the order of magnitude of the elastic wave-

length. Fig. 125 gives the diffraction image resulting from reflection at the surface of a vibrating cube of glass; the image is formed of a single circle, which is again an aggregate of individual interference points. This circle surrounds the two circles given at the same frequency with through illumination, as appears from

fig. 125 (b), in which the circle produced by reflection has been dotted in. The following figures (c) and (e) give the interference curves obtained by reflection at the  $YZ$  and  $XZ$  planes of a vibrating quartz cube. These consist of an obliquely placed ellipse and an ellipse-like figure respectively, and, as is shown in

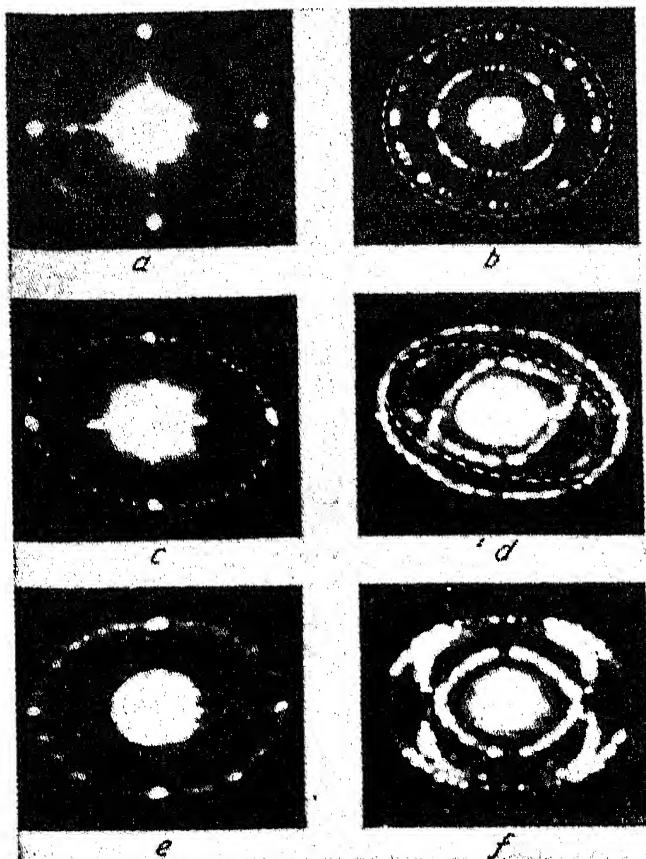


FIG. 125. Diffraction images produced by reflection of light at the surface of a vibrating glass tube (a), (b), and a quartz cube (c)-(f) (Schaefer and Bergmann).

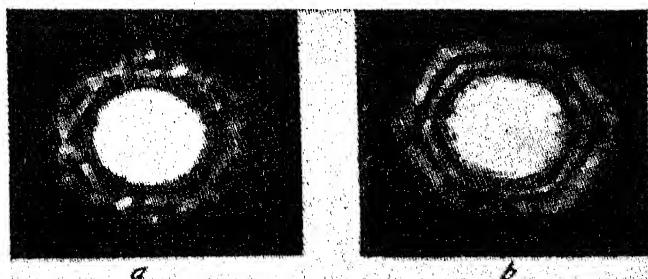


FIG. 126. Diffraction images produced by reflection of light at the surface of (a) a quartz crystal, and (b) a calc spar crystal, at right angles to the optical axis (Schaefer and Bergmann).

and *f*,\* likewise surround the images obtained by through illumination. Finally, fig. 126 (a) and (b) gives the diffraction images obtained with quartz and fluor spar by reflection at the surface normal to the optic axis; these again show the threefold symmetry to be expected. A theory of the production of diffraction images by the reflection of light at the surface of a vibrating body has been given by Ludloff (312-314). He considers, in addition to the elastic waves travelling in the interior of the body, the inhomogeneities

\* These photographs were taken by reflection of the light at the lower side of a vibrating cube of quartz, so that the interference curves for through illumination and reflection could be photographed together.

geneous surface waves, which are responsible for the diffraction in reflection. This leads first of all to a completion of the form-frequency surface, inasmuch as imaginary values of the propagation vector are now admitted. But we then have the whole two-dimensional manifold of plane waves, the propagation vector of which ends on the completed form-frequency surface, taking effect at the reflecting boundary surface, and contributing as a whole to the interference figure. This means that each of these possible plane waves, like every line grating, diffracts incident monochromatic light at an angle corresponding to its elastic wave-length, and that we get on the image plane a two-dimensional continuum of interference points and no interference curves, hence there must further be a selection principle in operation, whereby the number of the interference points is limited. This selection cannot come about in this case, as it did in the case of through illumination, for optical reasons. There the separation was effected by application of Bragg's law of reflection. In the present case of the reflecting surface the Bragg reflection planes degenerate as it were to straight lines, so that an interference angle may be stated for every elastic wave-length  $A$  and every light wave-length  $\lambda$ . Ludloff's theory now leads to the fact that the necessary choice is given by an elastic condition, namely, by the condition of the freedom of forces at the boundary of the vibrating body. Only a quite definite compound of transverse and longitudinal or inhomogeneous waves guarantees outward vibrations of the surface, which result in freedom of forces. We have in addition to the equation for the form-frequency surface a further equation given by the analysis, and containing the surface condition. It would take us too far to go into all these details at length, and we must be content to refer to the original papers of Ludloff (302-304). Success has certainly been obtained in calculating theoretically the interference curves obtained experimentally by reflection from quartz. For the case of an isotropic body in the form of a vibrating cube, we get an interference curve of circular form, the radius of which is 1.1 to 1.2 times, according to the value of the Poisson ratio, that of the transverse circle obtained with through illumination. If we take thinner plates, the thickness of which is of the order of the elastic wave-length, we find that theoretically two, and in certain circumstances even several, circles are formed. Fig. 127 shows the dependence of the ratio

of the radii of the transverse circle ( $r_{tr}$ ) and the reflection circle ( $r$ ) upon the ratio  $\Lambda/2h_1$ ,  $2h_1$  being the thickness of the vibrating plate, and  $\sigma = \frac{1}{2}$  and  $\frac{1}{4}$  respectively the Poisson ratios. From this we see that only when  $\Lambda/2h_1 = 0$ , that is when  $2h_1$  is very great, do we get a single circle formed by reflection, this being larger than the transverse circle. In the case of thinner plates this circle is split up into two. Schaefer and Bergmann (48) were also able to show this experimentally, as appears from the two photographs of fig. 128, in which two and even three circles respectively are clearly recognizable. The photographs were taken with a quartz glass plate 1 mm thick ( $\sigma = 0.17$ ) at elastic frequencies of 7477 and 5485 kHz. In the latter case the ratio  $\Lambda/2h_1$  almost reaches the value 1. We may finally mention that the vibrating surface of a metal plate excited piezoelectrically also gives circles by reflection, so that we here have a method for the elastic investigation of small samples of metal, alloys, etc.

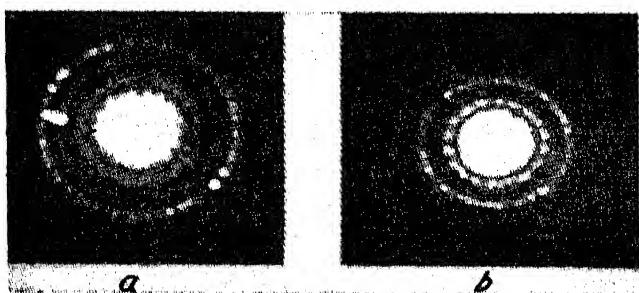


FIG. 128. Diffraction images produced by reflection of light at the surface of a thin vibrating glass plate at different frequencies (Schaefer and Bergmann).

cemented to it, and made visible by the method of ordinary light, we are able to measure the sound wave-length of the longitudinal wave. If the vibrating block of glass is examined between crossed Nicols, a sound-wave grating with a smaller constant is seen with suitable elastic excitation; this is regarded by Hiedemann and Hoesch as due to the transverse wave. The grating constant and so the wave-length of the

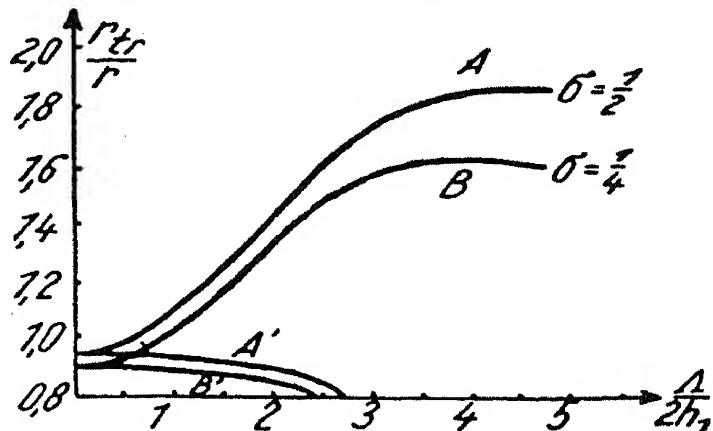


FIG. 127. Radius of the interference circle as a function of the wave-length along the surface (Ludloff).

The elastic constants of solid bodies have been investigated ultrasonically by a number of other workers also. Hiedemann and Hoesch (201, 209 to 211) set up a sound wave in a glass block by means of a piezocrystal the sound-wave grating directly by secondary interferences. Using

the sound-wave grating with a smaller constant is seen with suitable elastic excitation; this is regarded by Hiedemann and Hoesch as due to the transverse wave. The grating constant and so the wave-length of the

transverse wave can likewise be measured directly. It is here important that the electrical vector of the incident polarized light should be at right angles to the direction of propagation of the transverse wave. This agrees with the considerations put forward on p. 167 concerning the visibility of the diffraction phenomenon produced by the transverse wave. Hiedemann (201) interprets the observation of the transverse-wave grating between crossed Nicols as the rendering visible by double refraction of the positions of maximum pressure strain. This interpretation does not quite explain the phenomenon, as is already evident from the fact that the observation can only be made with the plane of polarization in a certain direction (*cf.* also p. 167). Since this method necessitates two sets of measurements, or two photographs of the two sound-wave gratings, it is more troublesome to carry out than the method of Schaefer and Bergmann, although the accuracy of the direct measurement of the grating constant is somewhat higher. Furthermore, the method fails, as is easily seen, in the case of both anisotropic and opaque bodies. No systematic investigation of elastic constants has hitherto been carried out in this way. It is clear that an image of a slit formed by ordinary light through the vibrating glass body gives us the ordinary diffraction images of Debye-Sears or Lucas-Biquard, which are formed by the longitudinal waves, when the slit is parallel to the direction of the propagation of the waves in the glass. If the vibrating body is between the crossed Nicols, we only get a doublet, that is to say the diffraction images of the first order formed by the transverse wave to right and left of the central image, which itself is blotted out. These phenomena were described by Hiedemann and Hoesch; they follow of necessity from the experiments of Schaefer and Bergmann, when the circular diaphragm is replaced by a slit, and the position of the polarizer and the analyser crossed to it is suitably chosen (414).

Quite a different way of determining ultrasonically the elastic constants of isotropic solids was given by Bär and Walti (27), and used by Bez-Bardili (56), in a somewhat modified form, for determining  $E$ ,  $\mu$ , and  $\sigma$  in the case of various metals and glass. If an ultrasonic wave travelling in a liquid meets a plane-parallel plate of an isotropic solid of thickness  $d$ , part of the wave is reflected and part transmitted. Maximum transmission takes place with vertical incidence if the relation  $n\Lambda'/2 = d$  holds, where

$n$  is a whole number and  $\Lambda'$  the sound-wave length in the plate. In this case the waves reflected at the point of emergence from the plate, after being again reflected at the point of entry, are in phase with the directly entering waves. If a ray of sound meets the plate obliquely at an angle  $\theta$  to the normal, and is refracted to an angle  $\Theta$  to the normal for the longitudinal wave, we have the relation

$$n\Lambda'/2 = d \cos \Theta$$

for the case of maximum transmission. Further, if  $\Lambda$  is the wave-length of sound in the liquid, we have for  $k$ , the index of refraction for sound passing from liquid to plate, the relation

$$k^2 = \Lambda/\Lambda' = \sin \theta/\sin \Theta,$$

and from these equations

$$\sin^2 \theta = k^2 - \left(\frac{n\Lambda}{2}\right)^2 \frac{1}{d^2}.$$

When the sound waves enter the plate obliquely, transverse waves are further produced in it, having a shorter wave-length  $\bar{\Lambda}'$ , for which the index of refraction  $\bar{k} = \Lambda/\bar{\Lambda}'$ . We then get a second relation:

$$\sin^2 \theta = \bar{k}^2 - \left(\frac{n\Lambda}{2}\right)^2 \frac{1}{d^2}.$$

These two equations give us  $k$  and  $\bar{k}$ , since all other values may be determined experimentally. The ratio  $\kappa = \bar{k}/k = \Lambda'/\bar{\Lambda}'$  gives us the Poisson ratios by means of the relation  $\sigma = \frac{\kappa^2 - 2}{2(\kappa^2 - 1)}$ . Bär and Walti did not use in their actual measurements plane-parallel plates, but wedges, and determined the maximum transmission of longitudinal and transverse waves for positions of different thickness, the intensity of the sound transmitted being measured by the strength of the diffraction effect on the light of the sound waves travelling in the liquid (see also p. 88).

The evaluation of  $k$  and  $\bar{k}$  is carried out graphically. It is, however, not quite easy to separate in the observations the longitudinal and transverse wave systems by choosing a suitable angle of incidence. Further, we get at certain angles of incidence so-called 'exchange' waves (*Wechselwellen*), which are produced by the transverse wave, generated by reflection at the farther wall

of a longitudinal wave in the plate, interfering in phase, on meeting the front wall and being reflected again, with a second entrant ray. Fig. 129 shows the course of the rays in a plane parallel plate, the full lines denoting longitudinal, and the dotted lines transverse waves. The emergent rays 1 and 5 come from the longitudinal waves in the plate, 4 and 6 from the transverse, and 2 and 3 from the exchange waves.

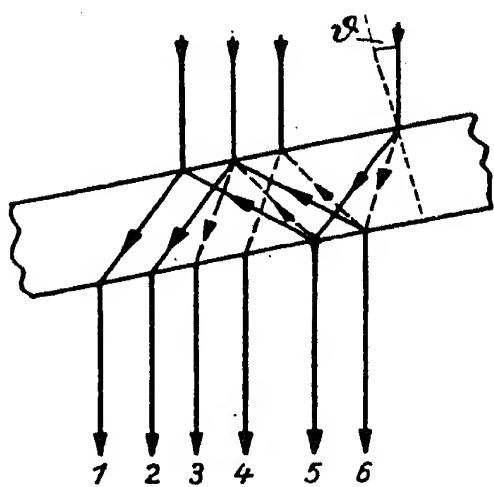


FIG. 129. Path of sound rays meeting a plane-parallel plate obliquely.

As we have already mentioned, Bez-Bardili (56) measured the elastic constants of solids in a quite similar manner. For this purpose he sent an ultrasonic ray of known velocity through a liquid, and made its path visible on a screen by means of the circular diaphragm method of Bär and Meyer (see p. 87); a plane parallel plate of the substance to be investigated is put in the liquid, and arranged

so as to be set at a measured angle to the sound wave. Fig. 130 gives a very beautiful picture of the parallel displacement of an ultrasonic wave in passing through an aluminium plate 10 mm thick. The partial reflection is also readily recognizable. The limiting angle of total reflection is observed both for longitudinal and transverse waves, and the velocity of sound then calculated for the two sorts of waves. Bez-Bardili further determined the velocity of sound from the maxima of the plate's transmission of the two waves in relation to the angle of incidence, using a similar method to the turning wedge of Bär and Walti. Bez-Bardili calculated from the two sound velocities the elastic constants of Al, Fe, Cu, brass, and glass, with an accuracy of about 1 per cent.

We close this chapter by a reference to a method given by Bergmann and Fues (50) for determining ultrasonically what are called the 'elasto-optical' constants of transparent isotropic bodies by means of ultrasonics. These constants are  $p$  and  $p'$ , which determine the double refraction produced in solids by elastic deformation, according to the theory of Neumann and Voigt. We denote by  $n_s$  the index of refraction of the body, originally isotropic but rendered birefringent by pressure, for a monochromatic linearly polarized wave, which travels in a direction

perpendicular to that of the pressure, and also has its electric vector at right angles to this direction;  $n_p$  is the index of refraction for a polarized ray of light having the same direction, but vibrating parallel to the direction of the pressure. We then have the well-

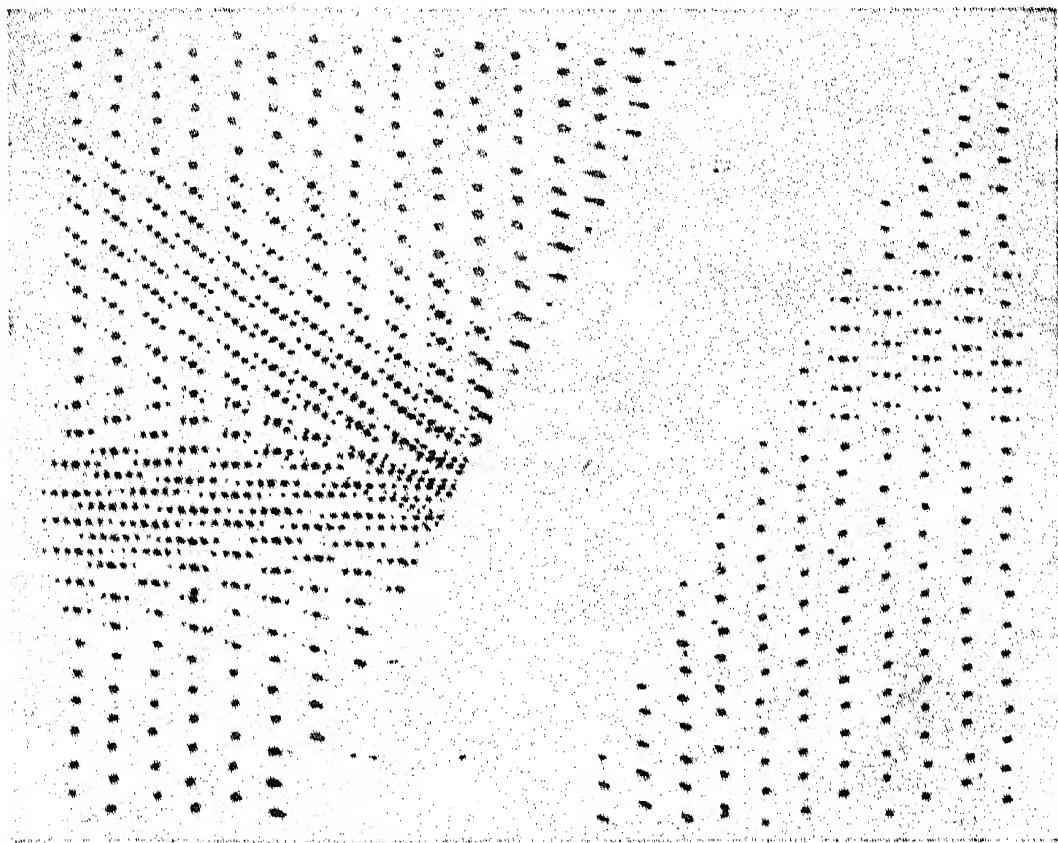


FIG. 130. Path of an ultrasonic wave coming from the left through a plane parallel aluminium plate 1 cm thick (photograph by Bez-Bardili, method of Bär and Meyer).

known expression for the amount of double refraction given by the following equation,\*

$$n_p - n_s = \pm \frac{nP}{E} (1 + \sigma) (p' - p)$$

( $P$  = pressure,  $E$  = modulus of elasticity,  $\sigma$  = Poisson's ratio). If we produce a wave of pure compression in a glass tube, that is if we send through it a longitudinal ultrasonic wave, a beam of light sent through it in a direction at right angles will give, as Fues was able to show theoretically, light intensities  $J_{\perp}$  and  $J_{\parallel}$  respectively in the first order spectra according as the electric vector of the light is at right angles or parallel to the phase plane of the elastic wave, and we get the ratio  $J_{\perp}/J_{\parallel} = (p'/p)^2$ .

\* See Coker and Filon, *Photo-elasticity* (Cambridge, 1931), p. 190 ff.

$J_{\perp}$  and  $J_{\parallel}$  may be easily determined experimentally as follows. An image of a slit is formed through the vibrating glass tube on a photographic plate, and a Wollaston prism is put in the path of the rays in correct orientation. We then get on the plate two images of the slit close above one another, the light of which is polarized at right angles and parallel to the direction of the slit, and hence also to the wave front of the elastic wave. If the glass cube is only allowed to vibrate strongly enough to produce the spectra of the first order, the light intensities of the two images of the slit are different according to the nature of the glass used, and may be measured photometrically. Table XXI shows the experimental values of the ratio  $J_{\perp}/J_{\parallel}$  for five different optical glasses of Schott and Gen ; the density is also given in the table.

TABLE XXI

	BK7	BLF1	BaSF2	SF4	SFS1
$\gamma_{\perp}/\gamma_{\parallel}$	0.64 2.52	0.72 3.10	0.86 3.97	1.02 4.79	1.06 5.96

The change of  $J_{\perp}/J_{\parallel}$  with  $\rho$  is the same in nature as that found by Pockels for  $(p'/p)^2$  for similar glasses. Experiments aiming at an absolute determination of  $p$  and  $p'$  are in progress. The following point is also instructive : with very heavy glasses,  $p'/p$ , that is the double refraction produced by mechanical strain, is very small. This produces an effect noticeable in the diffraction experiments of Schaefer and Bergmann on vibrating glass cubes by the fact that the outer circle is of very feeble intensity in the case of heavy glasses. This should be a further proof of the fact that this outer circle is actually formed by the elastic ultrasonic grating of the transverse wave.

## CHAPTER V

### FURTHER APPLICATIONS OF ULTRASONICS

(a) **The Ultrasonic Stroboscope.** When light is diffracted by a stationary ultrasonic wave the intensity of all spectra including that of zero order is intermittent with double the frequency of the sound, since the sound-wave grating producing diffraction is created and destroyed  $2N$  times a second (*cf.* p. 69). We therefore get modulation of the light by a frequency  $2N$ ; Bachem was the first to point out this fact. A stationary ultrasonic wave may

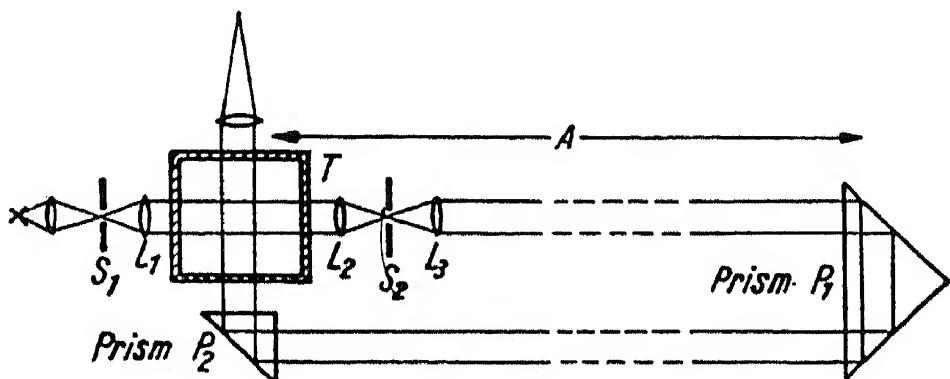


FIG. 131. Arrangement for measuring degree of modulation (Maercks).

therefore be used to produce a high-frequency modulation of light, applicable, say, for stroboscopic illumination. An arrangement of this sort gives a considerably better light output with simpler optical construction than the Kerr cell otherwise used for this purpose.

Becker, Hanle, and Maercks (39) have recently described arrangements of this sort for modulating light by an ultrasonic wave grating. Maercks (309) carried out measurements of this modulation, as well as a determination of the degree of modulation, by means of a photo cell, and was able to show that an almost 100 per cent. modulation of the diffracted light is obtained, whereas the light of the zero order is less completely modulated. An arrangement (fig. 131) used by Maercks for this purpose is interesting. The light proceeding from the brightly illuminated slit  $S_1$  is rendered parallel by the lens  $L_1$ , goes through the trough

$T$ , in which a stationary sound wave is generated parallel to the plane of the paper, and is collected by the lens  $L_2$  to form an image of the slit on the screen  $S_2$ . At this point the central image is either allowed to pass alone or screened off. The light having been made parallel again by a further lens  $L_3$ , it falls on a right-angled prism  $P_1$ , capable of displacement, and returns *via*  $P_2$  to pass once more through the sound wave in the trough. If the path of the light is altered by displacing the prism  $P_1$ , the intensity of the diffraction images produced by the second passage of the light through the sound wave, when the light of zero order is used, must be a minimum; if this second irradiation is not displaced in phase as compared with the first, on the other hand, a maximum if the path of the light results in a phase difference of  $90^\circ$ . But if, however, we use light of the higher order, the central image being screened out at  $S_2$ , matters are exactly reversed. The arrangement, therefore, gives us a simple method of measuring the velocity of light when the frequency of the sound is known. Maercks was further able to show that the light modulated by a stationary sound wave may be used for illuminating stroboscopically and so rendering visible a travelling ultrasonic wave. Bär (24) recently gave a full account of stroboscopic effects which appear when light is sent through to the sound wave.

It is naturally possible at once to replace the sound wave formed in a liquid by a stationary wave in a solid, and use it for the same purpose. This was practically realized by Hiedemann and Hoesch (213) by generating a stationary sound wave in a glass block by means of a piezoquartz cemented to it. If the vibrating block is placed between two crossed Nicols, we are able to use the longitudinal or transverse parts of the elastic wave, or both, for stroboscopic effects. For this purpose we have to use either the light from the central image alone for illuminating the periodic phenomenon under investigation, or that of the diffraction spectra with the other screened off. In the latter case we are again able to get 100 per cent. modulation of the light. Hiedemann and Hoesch also give a simple method in their paper for measuring the duration of brightness of different forms of ultrasonic stroboscope. Instead of using a vibrating mass of glass separately excited, we may, of course, also use a quartz crystal excited to its own natural vibration of a higher order.

These ultrasonic stroboscopes should be of especial value in

the region of very high frequencies, where the Kerr cell is known to give very high electric losses. A drawback of the ultrasonic stroboscope is, however, that it is always of use only for quite definite frequencies, namely, the elastic natural frequencies of the bodies used, and so a continuous change of frequency of the stroboscopic illumination is not possible.

If the arrangement is changed in such a way as to use the diffraction of light by a travelling sound wave, possible of course only in a liquid, and if the quartz vibration is modulated with a high frequency, the diffracted light varies with the amplitude of the quartz oscillation. This results in a light control method almost devoid of inertia, as first pointed out by Jeffree (234, 235) and recently by H. E. R. Becker (38). It is of importance that the quartz oscillations should be sufficiently damped. This may be obtained by using liquids of great acoustic 'hardness.' According to Becker's experiments, carbon tetrachloride has proved to be the best. This liquid has very small viscosity, resulting in low damping of the sound wave, high density (great acoustic hardness), and a low sound velocity, giving large angles of diffraction. The time constant of the arrangement is finally only dependent upon the time taken for the sound wave to travel. Both Jeffree and Becker give arrangements for modulation frequencies exceeding 1000 kHz, in which the travel time of the sound wave is eliminated. Quantitative measurements of the ratio of intensity of the light diffracted into the spectra to the light in the central image, as related to the energy supplied to the vibrating quartz, were carried out by Becker (36 a); he found an almost linear connection between the two.

(b) Ultrasonics in Television. The modulation of ultrasonic waves in liquids forms the basis of the 'Scophony' system of television. Television systems other than those using the cathode ray tube have the property that the illumination on the screen is inversely proportional to the definition standard, *i.e.* the number of elements in the picture. With the advent of modern high-definition standards, therefore, optical mechanical systems have been abandoned owing to the extremely poor illumination obtainable. The Scophony system overcomes this difficulty by using the diffraction of light-modulated ultrasonic waves, giving a screen illumination inversely proportional to the square root of the definition.

Simple optical-mechanical systems other than that of Scophony, consist essentially of three distinct components: the light source, the light modulator, and the scanning system. The Scophony system contains these three components, but

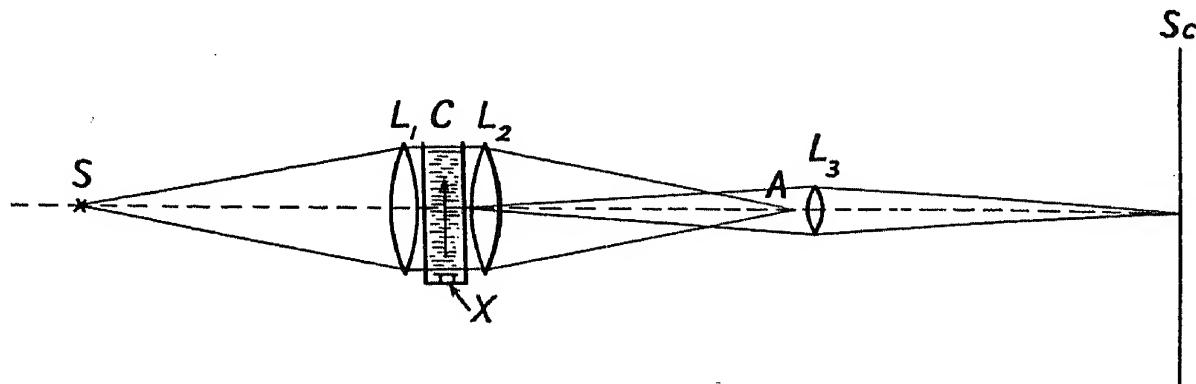


FIG. 131A. Modulation of ultrasonics for television.

the modulator and the scanning system can no longer be considered as distinct.

In fig. 131A,  $S$  is a light source of small dimensions, the light from which is rendered parallel by the lens  $L_1$  in passing through the ultrasonic cell  $C$  and then brought to a focus at  $A$  by the lens  $L_2$ . At  $A$  is placed a stop of such a size as just to obscure the image of the source. When ultrasonic waves are

made to pass through the cell by exciting the crystal  $X$ , diffraction images of the source are formed on either side of the stop. A lens  $L_3$  is placed so as to collect the light in these side images and form an image of the cell on a screen  $Sc$ . The screen will

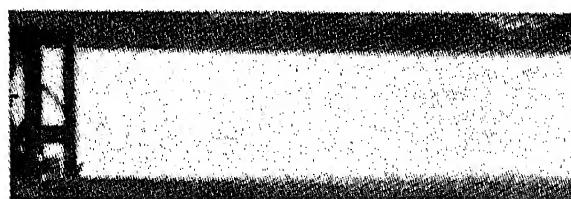


FIG. 131B. Photograph of screen image in 131A.

not be illuminated, therefore, until the cell is excited, when there will appear on the screen an image of the actual sound field in the liquid. Fig. 131B shows a photograph obtained by placing a photographic plate in place of the screen.

The illumination of the image on the screen can be made to bear an approximately linear relationship to the excitation voltage. If this voltage is now modulated with picture signals, at any instant the intensity of the image will be modulated along the length of the image, since the waves are travelling uniformly in the direction shown by the arrow. Thus though the image

of the cell is stationary the image of the waves and their modulation is moving with uniform velocity across the screen.

The first function of the high-speed mechanical scanner is to sweep the image of the cell across the screen at such a speed and in such a direction that the image of the waves is stationary on the screen. The second function is obviously to repeat the scanning movement once for every line of the picture. Generalizing, therefore, the ultrasonic cell performs the operation of transforming a time-distributed function into a spatial distribu-

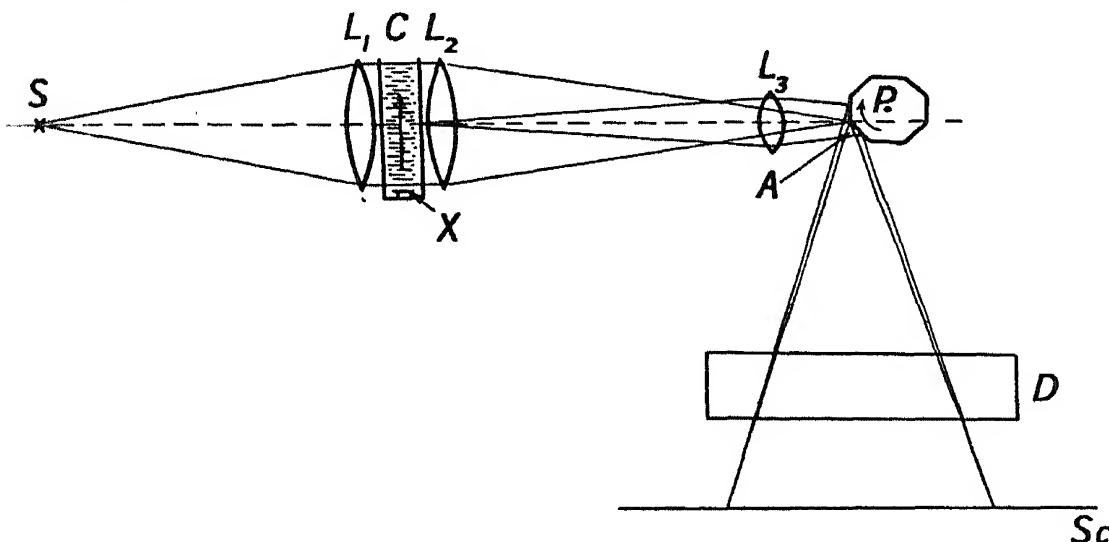


FIG. 131C. Scophony television apparatus.

tion, at the same time converting this spatial function into light variations.

It is evident that the cell may be of any length up to that equivalent to a full line (this corresponds to approximately 10 cm for a liquid in which the speed of propagation is 1000 m/sec). Since there are roughly 500 elements in a complete line on the standard used in this country, this system affords an increase in illumination up to five-hundredfold over the simple systems. The practical arrangement in its simplest form is shown in fig. 131C. *P* is the high-speed scanning member consisting of a metal polygon with polished faces. The low-speed scanning member is indicated at *D*, operating, of course, at right angles to *P*.

The ultrasonic cell is also being used to replace the high-speed scanning member *P* in fig. 131C. Only a bare outline of the principle used will be given here. Referring again to fig. 131A, let the cell be modulated by periodic pulses of short duration, the excitation being zero between the pulses. On

the screen will appear a series of equally spaced spots of light travelling uniformly across the screen. If the cell length is adjusted so that the time of travel of a wave along its length is equal to the period of the pulses, a single spot only will appear on the screen at any instant. At the end of a sweep the spot apparently returns instantaneously to the beginning of the sweep.

This arrangement constitutes a scanning system, and this form of disturbance in the liquid is termed a wave slot. For a complete survey of the applications of this device the reader is referred to Dr Okolicsanyi's exhaustive paper (336a).

The possibilities of the ultrasonic diffraction cell have by no means been exhausted. The properties of the cell, such as its simplicity from the optical standpoint, and its characteristic of constant time delay irrespective of frequency, render it a unique and invaluable instrument in the field of optical mechanical television.

(c) Ultrasonics as Means of Communication. One of the first technical applications of ultrasonics was to sound signalling. The use of high-frequency sound waves has the great advantage that these waves are very easily got into a beam, which is of importance for signalling in a given direction. The sound wave-length being so small, a mirror of convenient dimensions may be used when we have a point source, as the end of a magnetostriction rod; plate-shaped generators, such as quartz plates vibrating in thickness, magnetostriction rods with plates on their ends, radiate the waves in a direction approximately at right angles to the surface of the plate. The sound field in front of the plate has a decided directional characteristic, which is narrower, the greater the radius of the vibrating plate as compared with the wave-length radiated. For a circular piston membrane of radius  $R$ , the half-apex angle of the cone  $\theta$ , within which almost the whole of the sound is radiated away, is given by the approximate formula  $\sin \theta = 0.61\Lambda/R$ . A circular plate of 24 cm diameter radiates sound of a frequency of 30 kHz in water in a cone of an angle of about  $28^\circ$ ; at 300 kHz a plate of 7 cm diameter is already sufficient to confine the sound within an angle of  $5^\circ$ . A little consideration shows that conditions of this sort are never attained in the audible range. A further advantage of using ultrasonics, to which we have already drawn attention on p. 44, is the fact that very great intensities may be radiated without

the amplitude of the source becoming too great. Radiation of intensity 0.3 watt per square centimetre in water at 40 kHz requires an amplitude of vibration of only  $0.27 \times 10^{-3}$  mm, this already becoming  $21.6 \times 10^{-3}$  mm at 500 Hz; in air the corresponding values are  $15.4 \times 10^{-3}$  and 1.23 mm respectively—that is to say, the acoustic vibrator has a decidedly greater strain put on it. These last figures also show how comparatively unsuited air is as a medium for conducting sound. To this we must add the great absorption of ultrasonics in air as compared with water. Table XXII gives, for four different frequencies, the distances  $x$  in air and water after passage of which the sound intensity is reduced to one-half; hence signalling by ultrasonics is practically confined to water.

TABLE XXII

*Range of Ultrasonics in Air and Water at different Frequencies*

Medium	$N = 10$	100	500	1000 kHz
Air . .	$x = 220$ m	220 cm	4.8 cm	2.2 cm
Water . .	$x = 400$ km	4 km	160 m	40 m

Richardson (391, 391 a) was the first in the field in 1912 with two patents suggesting the possibility of using submarine ultrasonic transmitters for detecting the presence of icebergs. The first practical success was obtained in the years 1914–1918 by Chilowsky, and above all Langevin (283, 284, 287), whose first object was that of detecting the approach of submerged submarines by means of ultrasonics. Langevin, using a condenser telephone with mica dielectric at a frequency of 100 kHz, attained a range of 2000 metres in sea-water; he then proceeded to make the first use of the piezoelectric effect in the construction of a submarine transmitter. Fig. 132 gives a section of such transmitter, as built by the French firm of S.C.A.M., Paris, to the designs of Langevin and Florisson (144). Since the object is to radiate the sound from as large a surface as possible, and since the necessary quartz plates would be very costly on account of their size, the vibrating system is a combination of two steel plates  $b$  and  $c$ , each 30 mm thick and about 25 cm diameter, between which is cemented a mosaic  $a$  made up of single piezo-

quartz plates 2 mm thick. Since the velocity of sound is nearly the same in quartz and steel, the whole system vibrates like a single plate of thickness 6.2 cm, and generates an ultrasonic frequency of about 38,000 Hz. This arrangement has a further advantage besides its cheapness of construction, namely, that it resonates, as compared with a quartz plate of equal thickness

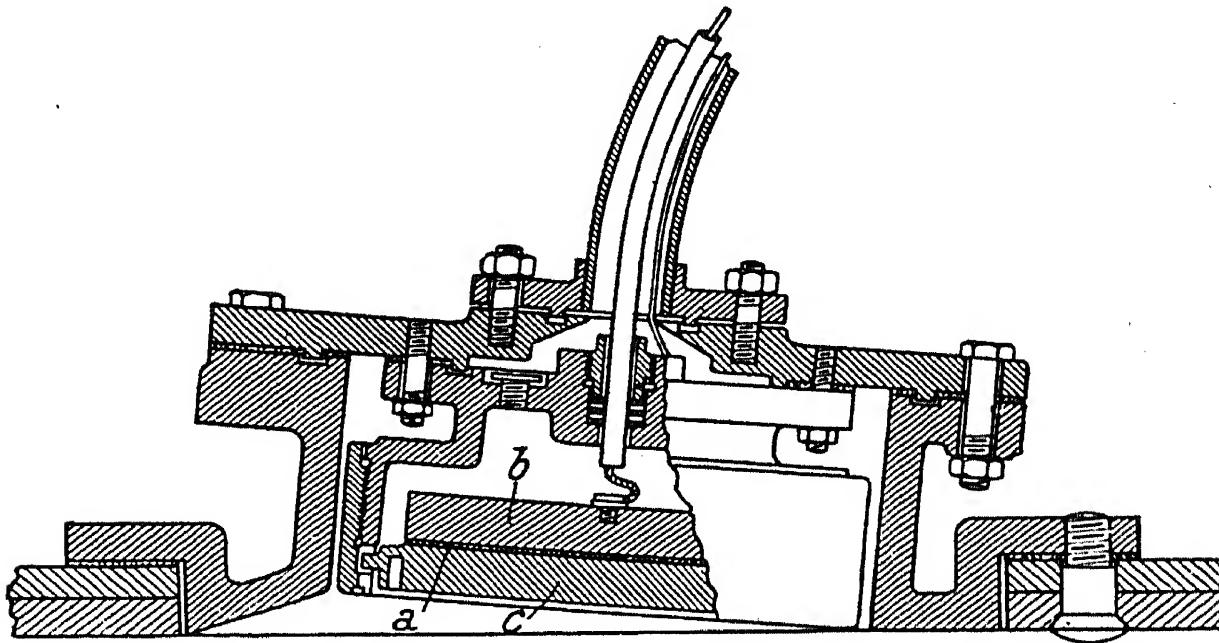


FIG. 132. Submarine transmitter for ultrasonics (Langevin-Florisson).

excited by the same field, with  $m$  times the amplitude, where  $m = \frac{\rho v^*}{\rho_0 v_0}$  ( $\rho$  = density and  $v$  = velocity of sound for the cemented metal plates;  $\rho_0$  = density and  $v_0$  = velocity of sound for quartz). For a combination of steel and quartz we get  $m = 25$ , hence the same output of sound may be generated by the combination of steel and quartz with considerably lower electrical voltages, which is of great importance in the practical use of the apparatus. The same construction may also be used as an ultrasonic receiver by connecting an amplifier and indicator to the two electrodes. The field of radiation sent out from sources of this sort in piston vibration has recently been calculated by King (245, 246), who took especial account of the influence of the viscosity of the transmitting medium on the range attainable. His calculations are in agreement with measurements, not yet published, by Boyle.

\* See the equation on p. 43.

The field of application of these submarine ultrasonic transmitters has three chief divisions. In the first place, they are used for signalling from ship to ship, especially by submerged submarines. Fig. 133 shows a design for this purpose of the Langevin-Florisson transmitter. The vibrating plate is vertical, and the whole apparatus can be turned about a vertical axis, and a device is provided for withdrawing it into the hull of the ship. Its range is 10 to 15 km; the accuracy with which the direction of the sound waves may be determined is about  $1^\circ$ . The signalling may be done either by Morse or by telephony, the quartz vibration being modulated by the speech frequencies. The second application is in determining the position of ships, submerged submarines, and so on by what is called the 'echo' principle. For this purpose ultrasonic signals are sent out at short intervals, the transmitter being changed over to a new set of connections, making it a receiver, immediately after each signal is sent out, when it then registers the returning ray of sound; in this way the time taken by the sound to travel to the object and back, and hence the distance of the object, can be found. The accuracy of measurement of distance by this method is about 1 per cent.  $\pm 50$  m. The third application of this method is for determining the depth of the sea. The method of echo sounding, first suggested by Behm (41), gains certain advantages by the use of ultrasonics. Apart from silent working, an advantage not to be underestimated when continuous sounding is necessary, it is possible to increase the number of soundings (7 to 15) in a second. It is further possible to take soundings in shallower water, and the accuracy of measurement is greater. Echo-sounding equipments with piezoelectric transmitters and receivers are manufactured in Germany by the Hamburg firm Debeg (400). The construction of the transmitter is essentially the same as that given in fig. 132. The transmitter is energized at a frequency of 37.5 kHz by a high-frequency impulse with a damped characteristic, and lasting about 1/1000 sec. The

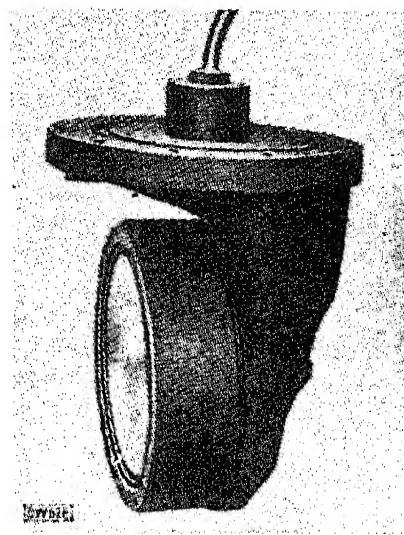


FIG. 133. Submarine transmitter for horizontal propagation (Langevin-Florisson).

peak voltage applied is about 6000 volts. The damping decrement when radiating in water is about 0.08. The alternating voltage generated by the echo in the transmitter, when switched over to reception, is sent to a valve amplifier, and thence to a device for measuring very short periods of time, consisting of a rotating gas-discharge lamp.

The Atlaswerke in Bremen (278, 280, 423) and the Electroacoustic in Kiel use in place of piezoelectric transmitters and receivers magnetostrictive apparatus, the natural frequency of which is between 20 and 30 kHz. This corresponds to

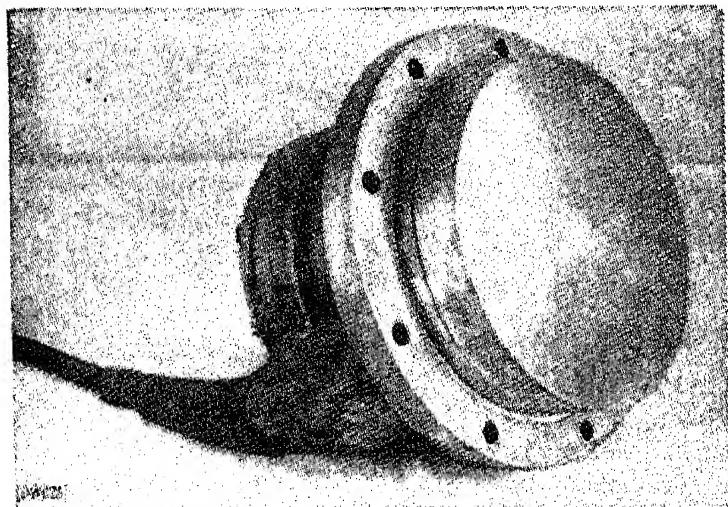


FIG. 134. Magnetostrictive submarine sound transmitter, designed by the firm Electroacoustic.

wave-lengths in sea-water between 7.5 and 5 cm. The magnetostrictive vibrators, the form shown in fig. 134 being that of Electroacoustic, are not continuously excited during echo sounding, but given an impulse like the striking of a tuning-fork, so that their vibration dies away at its natural frequency, sending out a short train of damped sound waves. The impulse is given electrically by discharging a condenser through the winding of the transmitter. The dispatch of the sound impulse, the reception of the reflected wave, and the indication of the depth of the water, are all carried out entirely automatically in modern equipment.

Fig. 134A gives an example of the mode of operation of such

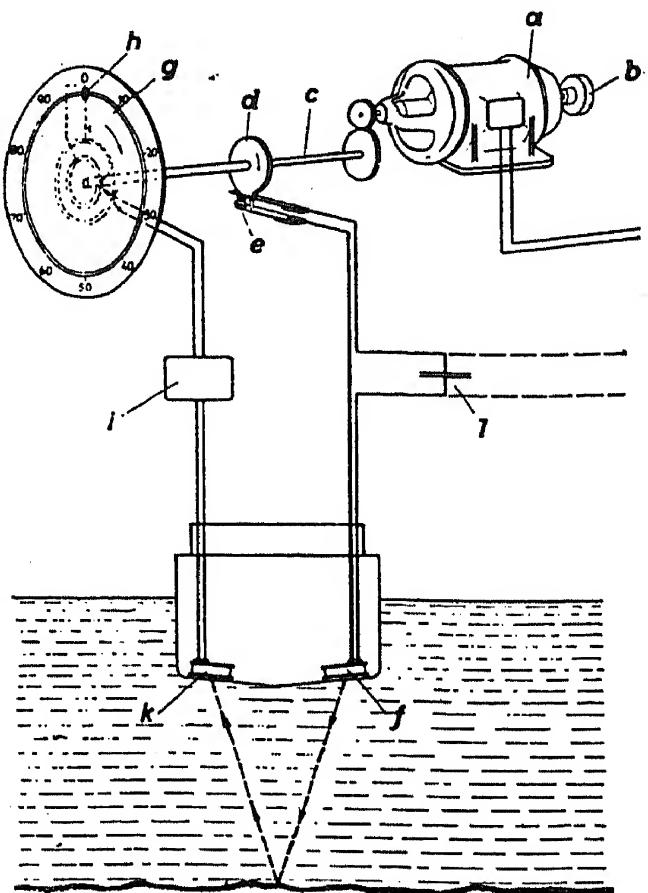


FIG. 134A. Mode of operation of the echo sounder of the Atlaswerke.

an echo sounder, in this case as constructed by the Atlaswerke. The momentary switching on of the transmitter *f* is effected by the switch *e*, operated by the rotating cam *d* at the moment when the glow-lamp *h*, fixed to the edge of the disc *g* rotating on the same shaft *c*, goes through the zero of the circular scale. The sound reflected from the bottom of the sea strikes the receiver *k* after a certain time, producing in it an alternating voltage, which is amplified in the amplifier *i* and causes the glow-lamp *h* to light up momentarily. In this way the glow-lamp is caused to light up several times in a second, the number depending on the rate of revolution of the shaft *c*, and the point at which it lights up depends upon the depth of the sea, which is read off in metres on the scale. The shaft *c* is driven by a motor *a* kept at constant speed by a centrifugal governor *b*.

This echo-sounding arrangement may be connected to a recording device named an 'echograph,' and we then have automatic registration of the sounding, whereby we get directly the profile of the sea bottom over which a ship has travelled (see, for example, 400, 442). It is even possible to deduce from the presence of multiple echoes the nature of the sea bottom, for example, whether it is sand, mud, or clay (400). Echo sounding has become of great importance in recent years in deep-sea fishing. In the first place, it is possible for the trawlers to find out more easily the right depth for fishing, and it is further possible to observe directly the presence of shoals of fish (423, 236).

Hayes (192), Slee (432), and Lübecke (305-307) have reviewed the various methods of echo sounding. Piezoelectric transmitters have also been used recently for submarine telephony by Marro (321). Kuntze (277) has carried out quite recently a thorough investigation of the generation and reception of ultrasonics modulated in the audible range by means of piezoquartz in air and metallic sound conductors. Yagi and Matsuo (478) carried out transmission experiments with unmodulated ultrasonics of a few 10,000 Hz up to distances of 200 metres. The ultrasonic wave arriving at the receiving station was superimposed on a sound frequency near it, and the beat tone was rectified and rendered audible. The transmission of ultrasonics through long wires of different materials was investigated by Sokoloff (434, 434 a). Since the damping of elastic vibration in solids is com-

paratively small, a not inconsiderable range may be attained in this way, and it is not impossible that this transmission of ultrasonics along wires may still attain a certain importance as a method of signalling.

(d) **Testing of Materials by Ultrasonics.** Metals in general exhibit a very good transmissibility for ultrasonics on account of their great acoustic hardness in so far as they are completely homogeneous. But if there are hollows, cracks, or other defects in homogeneity, a noticeable reflection and/or absorption of sound waves takes place at these points. This gives rise to the

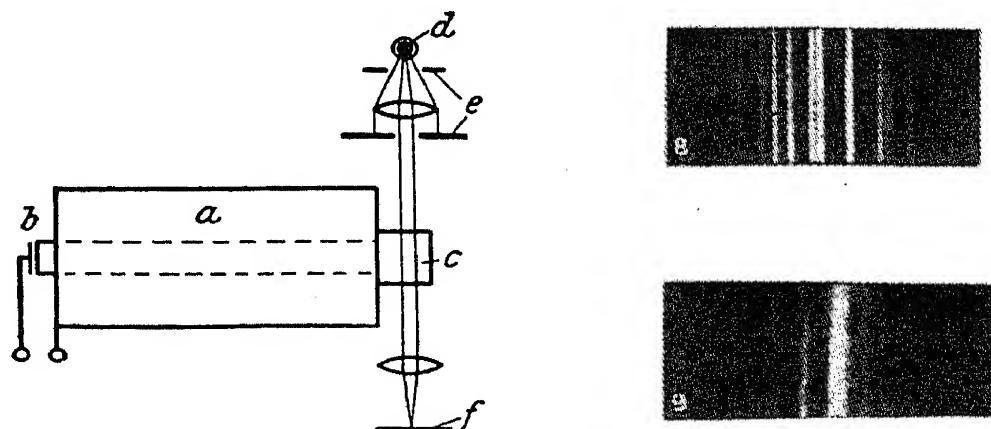


FIG. 135. Testing materials by diffraction of light by ultrasonic waves (Sokoloff).

possibility of testing material by ultrasonics. The first to point this out was Mühlhäuser (330) in a patent specification. He proposes to go over the mass of metal under test with a sound transmitter and receiver, and to draw conclusions concerning defects in the interior in the metal from the intensity of the sound transmitted by it.

Sokoloff (435) carried out practical experiments in this direction on large masses of steel in 1934. His experimental arrangement is represented diagrammatically in fig. 135. The piezoquartz *b* is pressed against a flat ground on the body *a* to be investigated, a drop of oil being interposed. On the opposite side we have a vessel *c* containing a liquid, into which the sound waves emerge after passing through the body. A slit *e*, illuminated by the light source *d*, is projected optically through the liquid on the screen *f*; we get there diffraction spectra, the intensity of which depends upon the strength of the sound wave entering the trough. If the sound beam is passed from point to point of the material, changes in the sound intensity in the trough *c*, given by

changes in the intensity of the diffraction spectra, give us an indication of inhomogeneities in the interior of the body, since these partly reflect and partly absorb the waves. The upper photograph of fig. 135 shows the diffraction images produced when the wave is sent through an homogeneous mass of metal, while the lower photograph is taken through non-homogeneous material. In order to detect inclusions or other defective spots smaller than the section of the sound beam, it is advantageous to use, in place of the slit, a row of circular apertures, images of which are formed on the screen through the liquid.

The more recent paper of Sokoloff (434 *a*) gives further details of his method of testing materials by ultrasonics. The transmission of sound through very thick blocks of metal (up to 1 m) necessitates considerable intensity of sound, which is generated by Sokoloff according to Langevin's principle (fig. 132). Special stress is to be laid on a good transmission of the ultrasonics to the body under investigation. In the case of bodies having a plane surface, it is sufficient to press the transmitter against it, using a film of oil between. If a larger piece of metal is to be examined all over, a more suitable arrangement is one in which mercury is used as a sound carrier. The point is that the acoustic resistance of the sound-transmitting material and of the material under investigation should be as nearly equal as possible, in order to avoid injurious reflection of the sound. The acoustic resistance of iron is about  $39 \times 10^5$  gm/cm sec, that of mercury  $19 \times 10^5$  gm/cm sec, so that, according to the equation given on p. 41, the reflecting power is about 11 per cent. as compared with 88 per cent. for the passage of sound from oil to iron.

Fig. 135A shows Sokoloff's experimental arrangement in section. *a* and *b* are two steel plates about 30 mm thick, between which are cemented a considerable number of quartz plates *q* of equal thickness. The drawing shows clearly how the upper steel plate is screwed as a sort of cover on to the cylindrical vessel *c*, which serves as a support for the whole transmitter. The alternating voltage is applied to plate through the vessel *c*, and to the plate *b* by the insulated conductor *f*. On the surface of the plate *a*, which radiates the sound waves, we have a layer of mercury *g*, which is prevented from escaping sideways by the ring *d*. The mercury serves to carry the sound to the material under investigation, *e*.

Sokoloff described the following very simple method of examining the sound waves transmitted through the material. On its surface, opposite to the sound transmitter pressed against its under side, we have a small flat basin *h* (fig. 135A), with a plane under surface, which rests on the material with a little oil between. The basin is filled with a layer, 4 to 7 mm thick, of oil or benzol. A parallel beam of light coming to the surface obliquely from a source *l* is reflected there to a screen *s*.

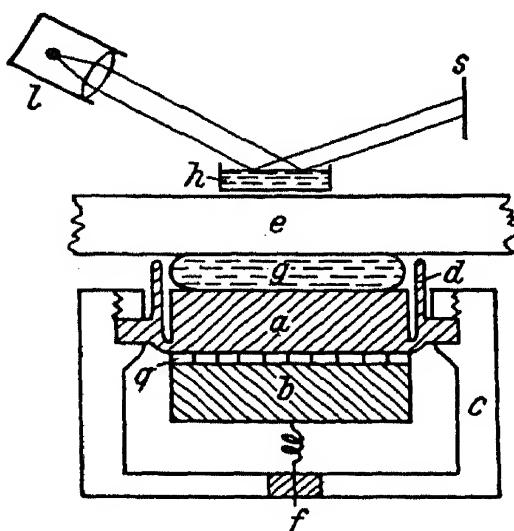


FIG. 135A. Experimental arrangement for testing materials by ultrasonics (Sokoloff).

The bright spot of light appearing there assumes various structures when the surface of the liquid is set in oscillation to a greater or less degree by the sound waves meeting it. The form of the spot of light, called by Sokoloff a 'sonogram,' thus gives us the means for deducing the intensity of the sound going through the material under test.

Finally, Sokoloff describes a further experimental arrangement in which the tedious and tiresome process of adjusting the source and indicator to the surface of the test-piece is dispensed with. The source is mounted in a

large flat vessel filled with oil in such a way as to send the sound vertically upwards. The beam may be limited in size by suitable diaphragms. At the point where this beam meets the liquid surface, an oblique ray of light is reflected to a screen. The test-piece is now pushed through the sound beam under the liquid at a distance of about one to two centimetres from its surface, the changes in the form of the light spot on the screen being all the time observed. This form of apparatus is said to allow test-pieces of considerable size to be gone over rapidly.

Further results of this very interesting method are not at present available, so it is not yet possible to come to any conclusion concerning its value for practical work.

(e) **Dispersive and Colloidal Effects of Ultrasonics.** Wood and Loomis (475) showed as early as 1927 that intense ultrasonic waves transform immiscible liquids such as water and oil, or water and mercury, into very stable emulsions. If two such

immiscible liquids, say water and benzol, are put in a test-tube one over the other and then acted on from below by powerful ultrasonics, the tube being dipped into an oil bath traversed by them, the benzol is seen to become quickly cloudy above the surface of separation, and the same effect, though not so rapid, appears in the water below the surface ; these two processes go on until an emulsion has been formed. The simplest supposition would be that the process of emulsification is due to particles of water being flung by the ultrasonic wave into the overlying benzol. However, systematic experiments by Richards (380, 388) showed this was not the only cause. He showed that emulsification is particularly strong at the boundary surfaces between liquid and vibrator, and also between liquid and the walls of the vessel. If, for example, a layer of benzol is put over some water in a tube, the walls of which are well wetted with water, and the whole arrangement then put into an ultrasonic field, the strongest formation of emulsion takes place on the walls of the vessel, while the boundary between the water and benzol still remains clear. The powerful effect of the vessel's wall also appears from the fact that some of the material of it is actually carried off by ultrasonic radiation in a finely divided form, and colloidally dispersed through the liquid. Thus optically empty water, exposed to ultrasonic radiation in very carefully cleaned vessels, shows, after a short time, a marked Tyndall effect (see ref. 180). Furthermore, air bubbles or dissolved gas present in the liquid, as well as the external pressure, may be of decisive importance as regards the production of an emulsion by ultrasonics. Investigations of this sort were undertaken by Rogowski and Söllner (396), who found that the emulsions produced are different according as a gas is present as third phase or not. Emulsions containing gas are much more easy to produce and much more stable than those which are gas free. Similar results were also reached by Sata (407).

Marinesco (314, 315) had already in 1933 dispersed different metals, such as Na, K, Cs, Hg, Pb, Zn, Sn, Cu, as well as fusible alloys and white phosphorus in alcohol, oil, and water by the action of ultrasonics. The metals and alloys of low melting-point were brought in contact with water or an oil of higher boiling-point in the molten condition, and the boundary surface exposed to ultrasonic radiation. The order of magnitude of the particles dispersed in this way is about  $0.5 \mu$ . Marinesco (314, 315)

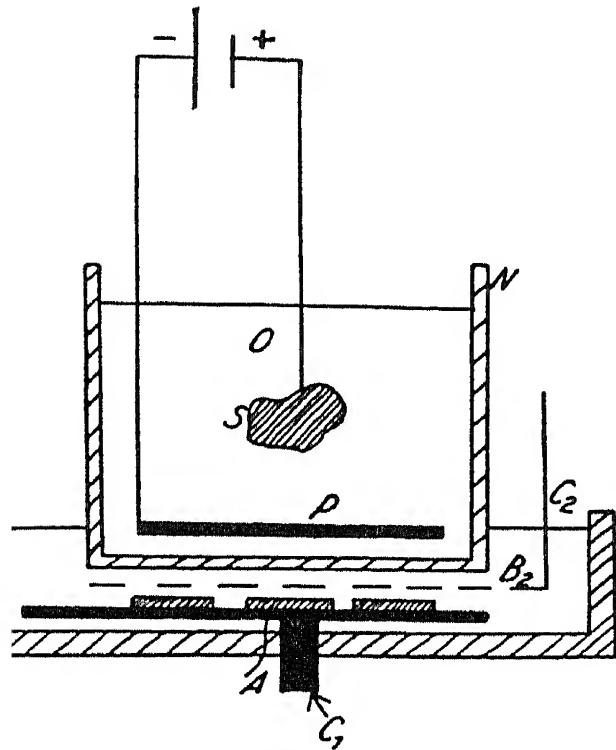
pictured the process of emulsion as follows. He supposed that when the ultrasonic wave meets the boundary between metal and water, the radiation pressure raises up a layer of metal of about the thickness of the amplitude of the wave into the water, and that this metal then breaks up into spherical particles of equal diameter. Alkali metals dispersed in petroleum or oil give rise to very inflammable dispersions. The production of water-petroleum emulsions, and its dependence on the intensity and frequency of the sound between 150 and 1160 kHz, were examined by Daniewski (121).

Using very great ultrasonic power at a frequency of 400 kHz, Rschevkin and Ostrowsky (399) have recently produced very fine emulsions of Hg, S, Sn, Bi, Pb, Cu, Ag, and also of various oils and paraffins in water. S, Pb, Sn, and Bi were obtained with particles as small as  $10^{-6}$  cm, so that they were true colloidal solutions, which showed a strong Tyndall effect. If the suspended particles have the form of rods or discs, ultrasonic waves of medium energy have a directive effect on the particles, their longest axis setting itself at right angles to the direction of propagation. This directive effect, which appears in the case even of true colloidal solutions, such for example as those of  $V_2O_5$  or  $Fe_2O_3$ , was investigated by Burger and Söllner (105 a).

The stabilizing effect of absorbed gases on mercury-water emulsions produced by ultrasonics was investigated by Bondy and Söllner (71), but no clear explanation can yet be given of it. The influence of ultrasonics on the colloidal solubility of metallic hydroxides, especially iron hydroxide, was investigated by Sata and Watanabe (408).

Important progress in the ultrasonic dispersions of metals in liquids was made by the work of Claus (113, 115). If a cathode is exposed during electrolysis to intensive ultrasonic radiation, the metal deposited there, which is already finally divided, is flung out into the liquid in a very highly dispersed form. Fig. 136 shows a section of one experimental apparatus used for the purpose. In the lower vessel we have under oil and resting on the electrode *A*, one or more equal piezoquartzes as ultrasonic sources, the upper quartz electrode being at *B*<sub>2</sub>, with a current connection *C*<sub>2</sub>. The vessel *N*, through the bottom of which the sound waves pass, contains a suitable electrolyte *O*, a horizontal cathode *P*, and the anode *S* consisting of the metal to be dispersed. Claus has

described another construction (fig. 137) suitable for technical use, in which the vibrational energy of the quartz plates  $Q$  is utilized more efficiently by pressing them directly against the metallic wall of the electrolytic vessel  $E$ , which also serves as cathode. According to the conditions of operation, the metal coming from the anode is deposited in a more or less finely divided form on the bottom of the vessel, or forms an emulsion of the



136. Arrangement for dispersing  
gels by ultrasonics during electro-  
lysis (Claus).

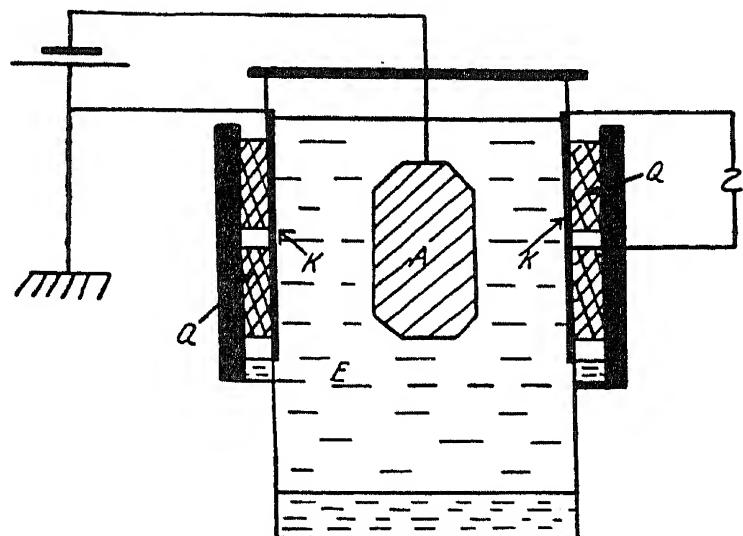


FIG. 137. Arrangement for dispersing metals by ultrasonics during electrolysis (Claus).

liquid. Fig. 138 shows the conditions of dispersion obtained by ultrasonic radiation, with and without electrolysis, for Hg and Ag, the photographs being  $\times 2000$ . The degree of dispersion of the substance depends chiefly on the electrode material and the surface of the cathode, as well as on the frequency and intensity of the sound waves. The most suitable cathode material is afforded by those metals which are difficult to plate, for example, Al, Ta, V2A steel, and the like, on which, therefore, the deposited metal coating adheres badly. The particles are smaller the smoother the surface of the cathode, the higher the frequency and intensity of the vibrations, and the smaller the current density and concentration of the electrolyte. It thus lies in our power to obtain, by changing the experimental conditions, dispersed

systems with particles of different sizes, and to disperse practically all metals which are able to be separated by electrolysis. Details and quantitative results are given at length in a publication of Claus and Schmidt (115 *a*). This method should certainly very soon acquire considerable importance for the manufacture of catalysts, sols, and such other substances whether for chemical or pharmaceutical purposes.

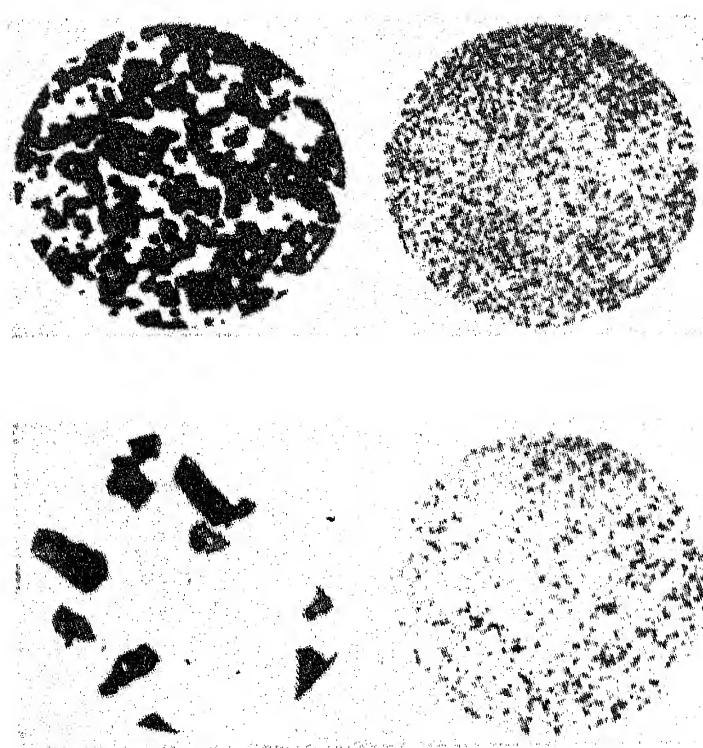


FIG. 138. Metals dispersed by ultrasonics without (left) and with (right) electrolysis; above mercury, below silver; magnification 2000 (Claus).

Claus devoted a further series of researches (112, 114) to the action of ultrasonic waves on photographic emulsions; and formed the conclusion that the homogeneity and stability of the emulsions are improved by the high-frequency vibrations, and that it is further possible to increase considerably the silver halide concentration, with a resulting rise in resolving power and sensibility. The injurious agglomeration of grains in the photographic film is not only prevented by action of ultrasonics, but when present even abolished. Table XXIII gives, for example, the number of agglomerations of grains counted on the same area of the photographic film after various treatments of the emulsion with ultrasonics.

TABLE XXIII

*Dependence of Grain Agglomeration in Photographic Emulsion on the Method of Treatment by Ultrasonics*

Method of Treatment	Number of Agglomerations
Action of the vibrations—	
during mixing process . . . . .	26
during ripening process . . . . .	11
during second ripening process . . . . .	15
during both ripening and second ripening . . . . .	8
during the whole process of manufacture . . . . .	14
on emulsion about to be poured . . . . .	14
Emulsion not acted on by ultrasonic vibrations	48

The use of high-frequency vibration on silver halide-gelatine emulsions allows the duration and temperature of the ripening process to be raised, without the formation of the disturbing veil effect which otherwise appears. The strong dispersive action of the ultrasonics, and the motion caused in the mixture by them, prevent the formation of local preferential points of ripening at the warmer parts of the walls and bottom of the vessel, and thus the formation of excessively marked nuclei. Finally, the colour sensitivity of the photographic emulsion may be considerably increased by sensitization with suitable dyes, inasmuch as the action of the ultrasonics leads to a greater fraction of the dye being utilized for colouring the grains.

It is, however, of especial importance that Claus also succeeded in getting pure precipitated silver halide, after sensitization, highly dispersed by ultrasonics in gelatine, the emulsion thus formed being in no way inferior in its photographic properties to highly sensitive silver bromide emulsions made in the ordinary way (114). Fig. 139 gives a comparison of the photographic films formed in different ways as seen under the microscope. The important technical manufacturing point is here the avoidance of the very tedious process of washing the emulsion, the time of manufacture thus being greatly shortened; further, since no foreign substances are added to the emulsion base, the durability of the films is improved. The photographic properties of such silver halide emulsions, formed by ultrasonics without chemical peptization, were investigated by Dangers (120).

Before we discuss a few further phenomena connected with this dispersive power of ultrasonics, we may shortly describe the

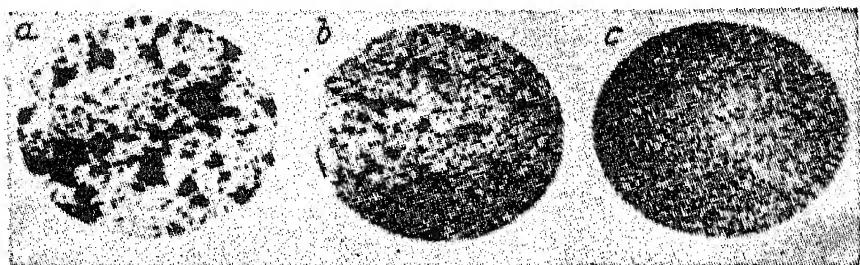


FIG. 139. Comparison of photographic films in which the bromide of silver was dispersed in the gelatine (a) by stirring, (b) by stirring and warming, and (c) by ultrasonics.

practical design of an ultrasonic dispersion apparatus as developed by Claus (115). This apparatus is suited not only for the experiments so far described, but may also be advantageously used for getting the effects described in the following pages. Fig. 140 gives a section of the apparatus. In the upper part of the vessel, which is made of insulating material, we have the piezo-electric quartz plates  $A_1$  and  $A_2$ , with their electrodes  $B_1$  and  $B_2$ , resting on the platform  $J$ . The upper vessel is filled with paraffin oil  $M$ , for conveying the vibrations to the objects to be treated, for example the vessel  $N$  containing the emulsion  $O$ . The paraffin oil may be cooled or heated by means of the pipes  $Q$ , and thus kept at a temperature suitable for the process in hand. The lower part of the vessel is filled with transformer oil and contains a Tesla transformer  $E$  for generating the high alternating voltages for the quartzes. The external coil of few turns  $F_1$ , and the three

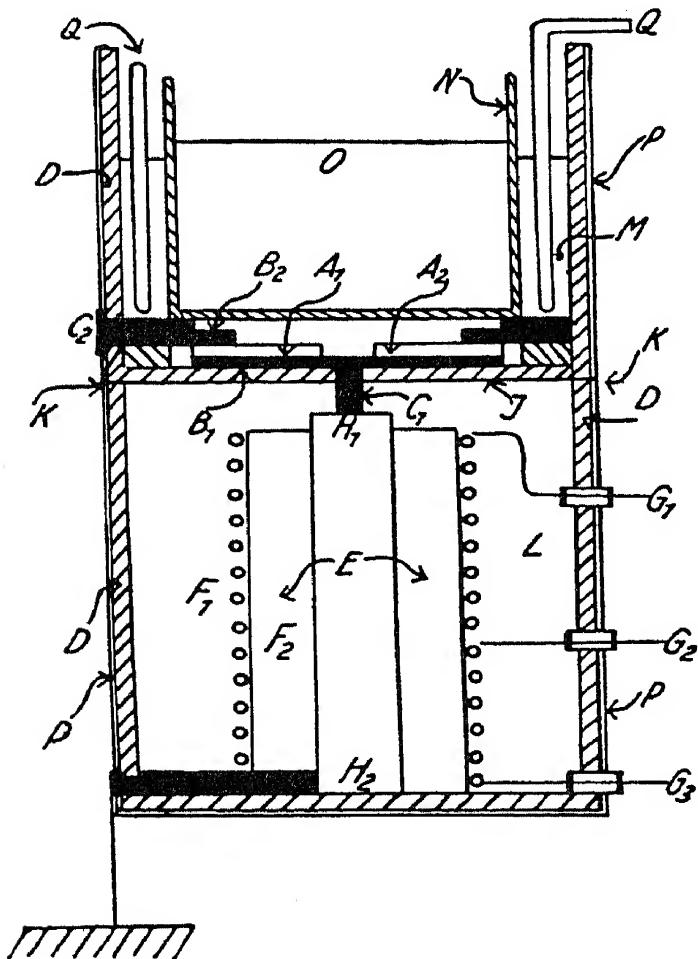


FIG. 140. Arrangement for generating intense ultrasonic waves in liquids (Claus).

part of the vessel is filled with transformer oil and contains a Tesla transformer  $E$  for generating the high alternating voltages for the quartzes. The external coil of few turns  $F_1$ , and the three

terminals  $G_1$ ,  $G_2$ ,  $G_3$ , are connected in the oscillation circuit of the valve oscillator, the inner coil  $F_2$  being connected by its two ends  $H_1$  and  $H_2$  to the electrodes  $A_1$  and  $A_2$  of the quartz. The whole apparatus is provided with a conducting earth shield. A somewhat more simple construction in this apparatus, without the built-in Tesla transformer, is shown in fig. 141. It is suitable for  $\frac{1}{2}$  to 3 litres of experimental liquid, and is made by the firm of Steeg and Reuter in Bad Homburg.

The experiments above described relate to the dispersing powers of ultrasonic waves at the boundary surfaces between different substances, but this shattering power of the waves seems in no way dependent on such boundaries between phases, but also to work on a molecular scale. Szalay (453) succeeded in splitting up a number of highly polymerized molecules by ultrasonics of a frequency of 722 kHz. Starch was transformed into dextrine; gum arabic, gelatine, etc., were decomposed. The chain of a molecule of starch was split into five or six fragments. The splitting effect of the ultrasonics was proved partly by measuring the viscosity, which decreases proportionally with the size of the molecule, and partly by chemical reactions. Szalay further succeeded in splitting up cane sugar into monosaccharides, and also in breaking up paraformaldehyde and hexamethylene tetramine. The two last substances show, after a short dose of ultrasonics, a slight increase in their power of reducing ammoniacal silver oxide solution. How this depolymerization by ultrasonics is brought about is still unexplained. The first necessity is to investigate the influence of the frequency of the sound.

The action of ultrasonics on gels was investigated in detail by Marinesco (313) and also Freundlich, Rogowski, and Söllner (153, 154). They found that thixotropic gels, for example iron or aluminium hydroxides, were liquefied by ultrasonic radiation



FIG. 141. Ultrasonic apparatus (Claus; carried out by Steeg and Reuter).

in exactly the same way as by shaking. No permanent change was produced in the gel. Liquefaction always takes place first at the surface air-gel. The swelling and peptization of gels in liquids of any sort is also accelerated by the action of ultrasonics. Further details in this field may be obtained from the detailed publication by Freundlich, Rogowski, and Söllner. Freundlich and Söllner (151) state in a recent publication that the liquefaction of thixotropic gels by ultrasonics depends essentially on the formation of cavities and their collapse in the sound beam. This is proved, for example, by increasing the external pressure, thereby preventing cavitation, when liquefaction no longer takes place.

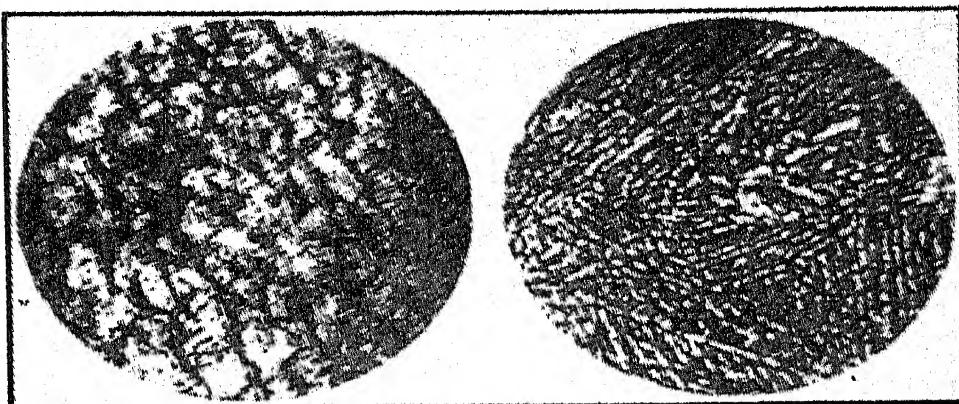
The emulsifying action of ultrasonics may become of especial importance in metallurgy. A great number of alloys are known, for example, Fe-Pb, Al-Cd, Al-Pb, Cu-Pb, Zn-Pb, etc., which are not miscible in the liquid state in any proportions, or in some cases only over part of the range. It is possible, according to Hertl (197), to keep the melt mixed up to the moment of solidification by means of ultrasonic waves, whereby the solid alloy acquires a very fine structure. Masing and Ritzau (333) have already succeeded, using low-frequency sound waves in this way, in getting lead added to aluminium to remain in a state of fine division in the latter metal.

Sokoloff (436) also investigated the action of ultrasonics on metallic melts of zinc, tin, and aluminium, and found that using about 80 watts in the frequency range of  $6 \times 10^5$  to  $4.5 \times 10^6$  Hz, the melts treated with ultrasonics solidified more quickly than those not so treated. Fig. 142 shows some photomicrographs of cast zinc, in which the effect of the ultrasonics on the structure is plainly seen, namely, to make it considerably finer grained and more in needle form.

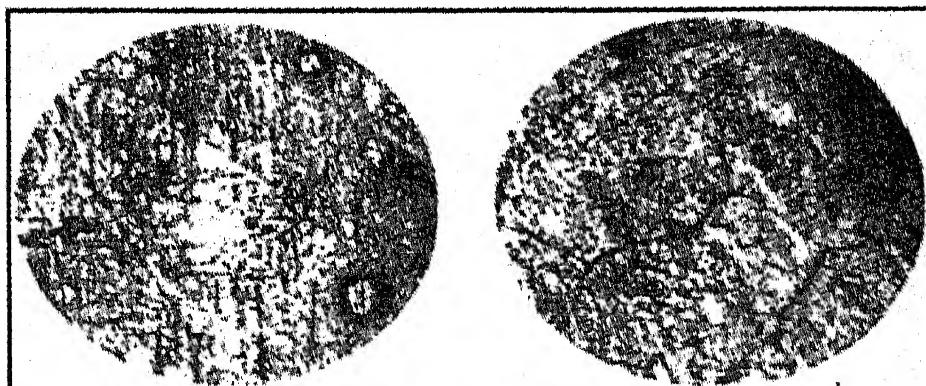
Apart from the effect on structure, there are some further points in connection with the action of ultrasonics on the solidification of solids, pointed out by Seemann (427). One may imagine influencing the formation of mixed crystals, or turning alloys normally consisting of heterogeneous crystals into mixed crystals by means of ultrasonics ; and so far no attempt has been made to act on compounds between metals by ultrasonics. Even if no great practical use is to be expected in all these problems, experiments would certainly result in a gain to our scientific knowledge.

Ultrasonics may also have considerable effect on the solid phase of a metal, for, as we know, any form of mechanical stress influences the transformation, separation, and decomposition processes

Frequency 700 kHz.  
(natural size).



Frequency 700 kHz.  
(magnification  $\times 300$ ).



Frequency 1200 kHz.  
(magnification  $\times 60$ ).



FIG. 142. Structure of cast zinc, (left) ordinary process, (right) treated by ultrasonics (Sokoloff).

going on in metallic materials. Hollmann and Bauch (219) were able to show that ultrasonics produced in a nickel rod a loosening of the molecular magnets, whereby the process of reversal of magnetization is considerably facilitated. We are, therefore,

dealing here with a loosening in the crystalline structure of ferromagnetic material by high-frequency sound waves.

This loosening of structure by ultrasonics is used by Mahoux (310) to improve and speed up the nitrogen hardening of steels. The rate of diffusion of nitrogen into steel is very small at the temperatures commonly used. For example, Meyer and Eilender (326) found that it took about forty-eight hours for nitrogen to penetrate at  $550^{\circ}$  C. to a depth of 1 mm into a steel of the composition 0.3 per cent. C., 1.12 per cent. Al, and 1.43 per cent. Mn. This depth of penetration is considerably increased, according to Mahoux and Guillet (180), under the action of high-frequency sound waves, and penetration also takes place more quickly. Other methods of improving steel could also be carried out more efficiently and at a lower temperature with the use of ultrasonics.

(f) **The Coagulating Action of Ultrasonics.** While ultrasonics have a strongly dispersive effect on emulsions and liquid sols, their effect on aerosols is the opposite, namely strong coagulation of the particles. The name aerosol is given to a dispersed system consisting of solid or liquid substances in a state of fine division in a gas ; in other words, mist, dust, smoke, etc.\* The difference in the action of ultrasonics on hydrosols and aerosols depends upon the fact that the first are much more stable, and that ultrasonics produce in liquids disruptive forces through cavitation ; the latter does not take place in gases, and aerosols are already in themselves less stable. It has been known for a long time that attractive and repulsive forces may appear between the vibrating particles in a field of sound vibration. This process was investigated experimentally and theoretically for spherical particles by König (269, 270), following up work by Bjerknes (68). This effect is partly responsible for the production of the dust figures in the Kundt tube. Brandt and Freund (92, 94-97) and Brandt and Hiedemann (100) were able to show that intense ultrasonics produced in aerosols almost instantaneous agglomeration and precipitation of the particles. These experiments were already referred to on p. 41 in discussing the way in which stationary sound waves are rendered visible in Kundt tubes. The experimental mists used were tobacco smoke, ammonium chloride, and later paraffin. The source of sound was a magnetostriction

\* See, for example, the general review of the subject by Brandt (93), Whytlaw-Gray and Patterson, *Smoke* (London, 1932).

device. Brandt and Freund succeeded in making the details of the process of precipitation visible by means of microphotographs with dark-field illumination. The experimental arrangement used is shown in fig. 143. The sound tube *A* is made up of three parts *A*, *B*, *C*, and at its lower end is an observation chamber *K*<sub>2</sub>.

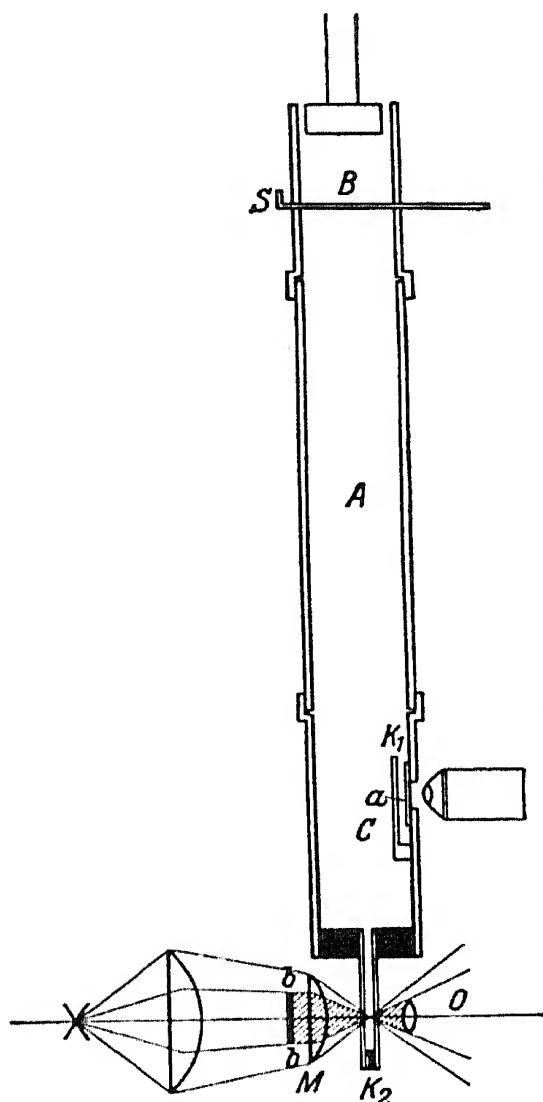


FIG. 143. Arrangement for investigating coagulation in gases by ultrasonics (Brandt and Freund).

Dark ground illumination is produced by the condenser *M*, *b* a circular diaphragm, and the front lens of the microscope objective is at *O*. The sound waves are generated at the upper end of the tube, and may be cut off by the slide *S*. The small chamber *K*<sub>1</sub> with a window *a* is used for observing the time of fall of the suspended particles. In this case the illumination is performed in the usual way at right angles to the direction of view. Fig. 144 gives eight successive microphotographs showing the coagulation of

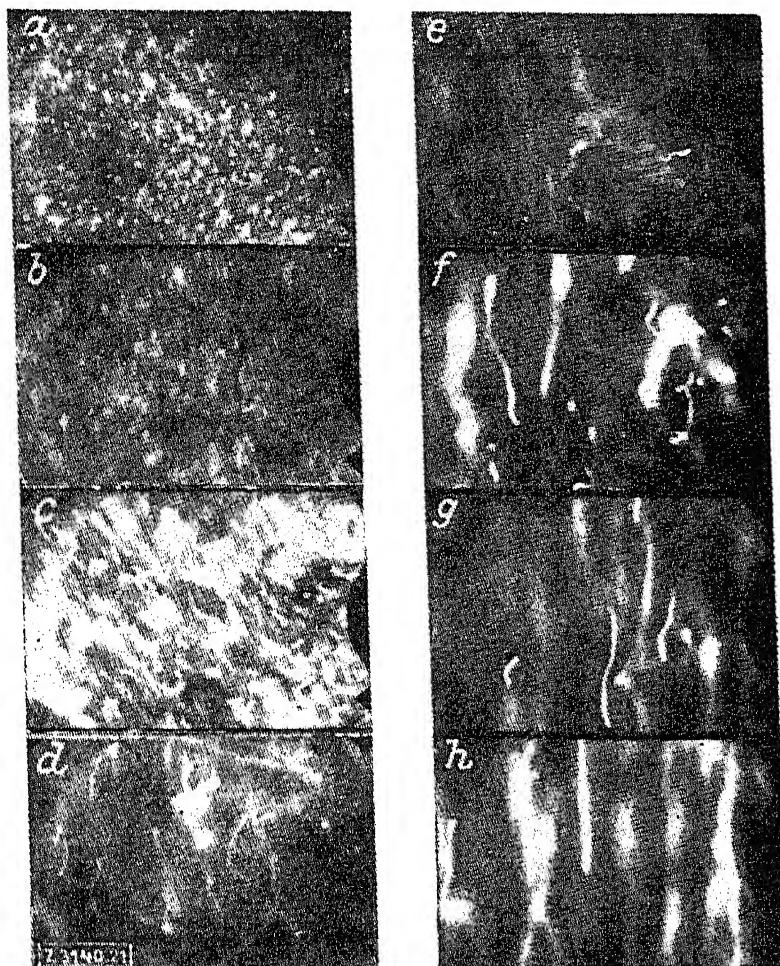


FIG. 144. Coagulation of smoke under the action of ultrasonics (Brandt and Freund).

the smoke. (a) shows the aerosol in its initial condition, in (b) the sound has just begun to take effect, and the particles are seen to be in vibration; the following photographs (c)–(f) show different phases of the coagulation, and we now see that the particles have become thicker and are moving in quite irregular paths through the field of view. The last two pictures (g) and (h) show the suspended material after the sound waves have been cut off. The coagulated particles fall through almost the whole field of view in the short period of the exposure (1/25 sec), whereas those not coagulated, as in the first picture, show no change of position. Brandt and Hiedemann distinguish two stages of coagulation as a result of these experiments. First the particles take part in the vibration of the gas, and in its flow between the loops and the nodes of vibration, whereby they are increased in size by collision, and the attractive force between them is increased. In the second stage the enlarged particles no longer take part in the sound vibrations, but describe irregular paths, during which they undergo new collisions with one another and the smaller particles, and are so further enlarged. The dependence of increase of particle size on amplitude  $a$  (measured in  $\mu$ ) for equal time of action, is given in Table XXIV, in which the coagulation is measured by the ratio of the mass  $m$  of the enlarged particle to the original mass  $m_0$ .

TABLE XXIV

*Dependence of Increase in Particle Size upon Amplitude of Sound in Coagulation by Ultrasonics*

Amplitude $a$	Mass Ratio $m/m_0$
0	1
9	2.1
18	8.7
36	13.6
54	200

The determination of increase in size was partly carried out by measurements of the rate of fall, and partly by an optical method in which the absorption of light by the mist was measured during the action of the ultrasonics.

The dependence of coagulation on frequency as well as the influence of hydrodynamic forces, etc., is dealt with in detail by

Brandt, Freund, and Hiedemann (99, 101, 202). Corresponding to every size of particle we have a certain frequency, up to which the particles still completely follow the sound vibrations of the medium, while at higher frequencies their amplitudes are smaller. For this reason, there is for any anisotropic aerosol a certain favourable range of frequency, depending on the particle size, in which the amplitudes of the particles are variable, resulting in collision and coagulation. At very high sound frequencies, this region favourable to 'orthokinetic' coagulation is left behind, and there remain only the hydrodynamic forces considered by Bjerknes.

The degree to which a particle in a stationary sound wave takes part in the acoustic vibration of the medium is given, as depending on frequency and radius of particle, by the following formula:

$$\frac{X_p}{X_g} = \frac{1}{\sqrt{\left(\frac{4\pi\rho r^2 N}{9\eta}\right)^2 + 1}}.$$

Here  $X_p$  is the amplitude of the particle,  $X_g$  the amplitude of the gas,  $r$  and  $\rho$  the radius and density of the particles

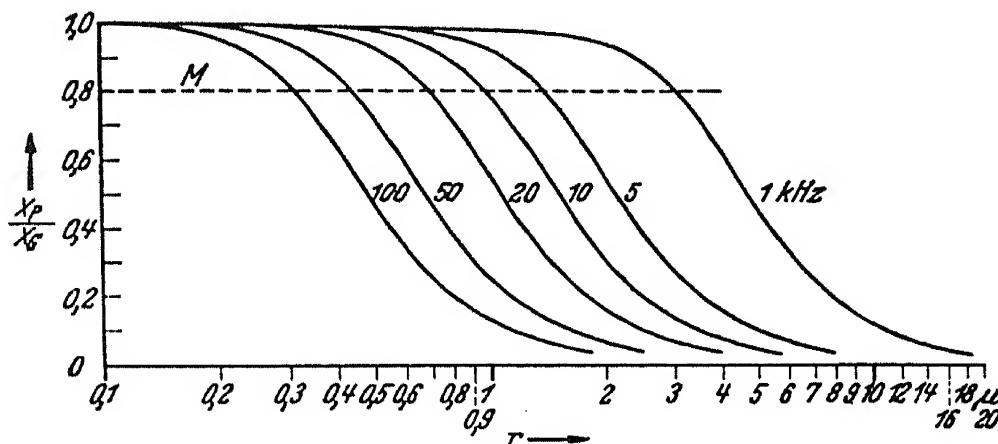


FIG. 145. Relation between amplitudes of particles and gas.  $X_p/X_g$  as depending on radius of particle at different frequencies.

respectively,  $N$  the sound frequency, and  $\eta$  the coefficient of viscosity.

The amplitude ratio  $X_p/X_g$  becomes smaller as particle radius and frequency become greater.  $r^2 N$  is therefore what determines the degree to which a particle takes part in the vibration of the gas. Fig. 145 represents graphically the relation between  $X_p/X_g$  and  $r$  for different frequencies  $N$ . The frequency range

between 5 and 50 kHz was found to be especially favourable for most aerosols.

In order to cause precipitation in aerosols during flow, Brandt, Freund, and Hiedemann used as sound source a Hartmann air-jet generator, built between two resonators through which the aerosol streams. According to these authors, 200 litres a minute of salammoniac smoke could be cleared up with an arrangement of this sort. Among older experiments in this field we may mention those of Patterson and Cawood (353), who observed the enlargement and precipitation of aerosol particles under the action of piezoelectric sound waves of 34 kHz, and also experiments by Pearson (354), which were already mentioned on p. 42. Gorbatschew and Severny (168) investigated the motion of a heavy drop in a sound field, and the ponderomotive forces coming into play. The question of the mechanism of ultrasonic coagulation in emulsions and suspensions is discussed by Söllner and Bondy (433). A theory of the coagulation of smoke under the action of frequencies so high that the particles no longer take part in the vibration of the medium is given by Andrade (5), taking account only of the hydrodynamic attractive forces between the particles. The formula deduced by Andrade for the rate of decrease of particles in 1 cc with time was tested experimentally by Parker (345) on magnesium oxide smoke, using ultrasonics of 220 kHz ; he was able to confirm it within certain limits.

(g) **The Degassing of Liquids and Fusions by Ultrasonics.** Boyle and Lehmann (76, 80, 82) were the first to observe that when ultrasonic waves of comparatively low energy are sent through liquids, gas bubbles are formed. Further investigations by Boyle and his co-workers (91) showed that these bubbles are produced by the union of microscopically small bubbles already present in a liquid. These bubbles are driven towards the nodes of a stationary sound wave, and may be used as a means of detecting such waves (459). Added to this is the fact that the expansions of the liquid in the wave give rise to negative pressures in the liquid, leading to the emergence of the gas dissolved in it, and the formation of bubbles. Boyle and Taylor (90) recognize as a further cause of bubble formation the phenomenon of cavitation, which consists in the formation of hollows by the liquid being torn apart. This formation of cavities may, according to Söllner (432 a), be rendered visible

by irradiating long layers of completely degassed liquid by powerful ultrasonics. We then get in the liquid zones of less transparency for light, and having a feebly glittering appearance ; these disappear again when the ultrasonics are cut off, without leaving bubbles behind. The gases dissolved in the liquid are able to escape into the spaces formed by cavitation, so that the effect of the sound wave is to degass the liquid. Bondy and Söllner (70) deal at length with the theory of cavitation produced in liquids by ultrasonics. In particular, they regard cavitation as responsible for the emulsifying action of sound waves. Cavitation, and hence the formation of bubbles in the liquid, depends greatly on the external pressure. This must not exceed a certain critical value if there is to be degassing. This critical pressure for water saturated with air is about 4.5 atmospheres according to Johnson (237) ; more recent investigations indicate that it is dependent on the frequency (437).

Quantitative measurements of the degassing of liquids by ultrasonics were first carried out by Sörensen (437), who found that the driving out of 1 cc of gas from water saturated by air required 51.2 kW at 194 kHz, 72.6 kW at 380 kHz, and 87.4 kW at 530 kHz. Degassing is thus strongly dependent upon frequency. A perceptible amount of degassing of oil could only be obtained at low frequency.

The possibility of using ultrasonics for degassing should be less important for liquids than for fused metals, where it is important to obtain the solid materials free from inclusions of gas. Proposals for degassing fused metals were made by Krüger and Koosmann (274), and also by Hertl (197). No practical experiments in this field have yet been published.

(h) **Chemical and Physical Effects of Ultrasonics.** The various workers who have made experiments on ultrasonics have observed a whole series of chemical effects, which will only be discussed very shortly in the following pages, since in a great number of cases a trustworthy explanation of these phenomena is not yet to hand. It is also frequently difficult to separate the purely chemical action of ultrasonics from a concomitant thermal effect. Richards and Loomis (88) found an increase in reaction velocity in the hydrolysis of dimethyl sulphate, in the Landolt reaction, and in the oxidation of potassium iodide. The latter reaction was confirmed by Beuthe (54) with observa-

tion of all necessary precautions. In about 20 cc of potassium iodide solution, 0.4 to 0.5 mg of iodine were separated in ten minutes by means of ultrasonics, a distinct yellow colour being produced. If the heating effect produced by the ultrasonic waves, namely to 55° C., was produced without ultrasonics in the same time, there was no separation of iodine. Beuthe detected also the following further reactions produced by ultrasonics: a  $\text{KMnO}_4$  solution of a faint pink colour (about 1/1000 normal) showed after ten minutes a colour change to brown, caused by the formation of hydrated manganese dioxide. A similar reducing effect took place in the case of  $\text{HgCl}_2$  to which ammonium oxalate had been added,  $\text{HgCl}$  being precipitated in one minute. The oxidation of aqueous solutions of dyes could also be observed. Dilute solutions of phenolphthalein, water-blue, sirius blue, and water-glass blue were partly rendered colourless, partly changed in colour. After ten minutes' action of ultrasonics on pure distilled water, the presence of hydrogen peroxide could be proved by titanyl sulphate. This last experiment gives rise to the supposition that the formation of  $\text{H}_2\text{O}_2$  is the primary process in all the reactions previously described, since they may all be caused by very small quantities of  $\text{H}_2\text{O}_2$ . Further experiments by Beuthe led to the result that  $\text{H}_2\text{O}_2$  is only formed in water saturated with oxygen or air, and this explains the fact that all the chemical reactions observed take place only in water containing air, if at the same time the formation of gas bubbles occurs. The only question is that of the source of the great energy necessary to dissociate the  $\text{O}_2$  molecules dissolved in the water in order to cause a formation of  $\text{H}_2\text{O}_2$ . Beuthe imagines this process to take place as follows: The vibratory motion of the gas bubbles produced by the ultrasonic wave causes  $\text{O}_2$  molecules to be ionized at the comparatively large boundary between liquid and gas, perhaps by the action of electric charges. The  $\text{O}$  atoms thus formed are then absorbed by the water with formation of  $\text{H}_2\text{O}_2$ . Further experiments of Beuthe have shown that nitrogen dissolved in water gives in the same way under the action of ultrasonic waves a formation of nitrous acid and ammonia.

Schmitt, Johnson, and Olson (421) arrived at quite similar results. A further reaction observed by them is the production of turbidity by separation of sulphur from  $\text{H}_2\text{S}$  solution, which

may also be explained as an oxidation. Particularly strong reaction is produced by ultrasonics in an aqueous solution of carbon tetrachloride in presence of potassium iodide and starch. The blue colour of the starch iodide appears immediately. These reactions also only appear when the solutions contain air. The reaction velocity is dependent on the external pressure, at first increasing somewhat with increase of pressure, and then falling again at higher pressures. Schmitt, Johnson, and Olson conclude from this fact that there is a certain critical size of gas bubbles at which the activation of the oxygen is particularly marked. Liu and Wu (291) carried out further experiments in this direction ; they also found that ultrasonic oxidation occurs only in the presence of oxygen, but their experiments showed, on the other hand, that the amount of  $H_2O_2$  formed during the action of the ultrasonics was too small to explain the yield of the reactions. They therefore assume that the oxygen is activated directly by the action of the ultrasonics.

Attention should be given in this connection to a paper by Smith (432), who investigated the pulsation vibrations of small gas bubbles under the action of alternating sound pressure. When their dimensions have a certain value, the bubbles vibrate in resonance, the effect being that the local mechanical stresses in the liquid may rise to 15,000 times the hydrostatic pressure. The resonance frequency of the gas bubbles depends on their radius, on the hydrostatic pressure and density of the liquid, on the ratio of the specific heats of the gases, and on the surface tension between the gas and liquid. It is not improbable that the chemical reactions are in part conditioned by these great concentrations of energy. Flosdorf, Chambers, and Malisoff (145) have investigated the oxidation processes in liquids caused by large sound energies in audible limits ; amongst other things they found that reaction of sound on sodium luminol gives chemiluminescence produced by the  $H_2O_2$ , most strongly marked at those points where the formation of gas bubbles and cavitation are strongest.

Richards and Loomis (388) found that labile substances such as  $NI_3$  explode in the liquid when subjected to ultrasonics. Whether this is a case of chemical or purely mechanical action is not yet settled. Marinesco (316), who recently repeated these experiments, ascribes the explosion to the gas bubbles suspended

in the liquid, which are heated up under the alternating sound pressure to a temperature exceeding the ignition point of  $\text{NI}_3$ , fulminate of mercury, etc. If the formation of gas bubbles is prevented these substances do not explode.

Further ultrasonic reactions which should be mentioned are the crystallization of supersaturated liquids, the explosive evaporation of superheated liquids, the lowering in the boiling-points of carbon tetrachloride, toluol, ether, and water, which may amount to  $2^\circ$  (388).

The action of ultrasonics on finished photographic films has been shown by Marinesco and Trillat (316 *a*, 318) to produce a slight fogging of unexposed plates; they also found that an exposed plate treated by ultrasonics before development shows stronger blackening than one not so treated. Marinesco and Reggiani (317) obtained systems of bands, after an exposure to sound of some minutes, on a photographic plate placed in a light-tight case filled with developer, and put in the path of a stationary ultrasonic wave. This photochemical action of ultrasonics is assumed by the authors to be due to activation by collisions between silver molecules. It is, however, not impossible that in these experiments the plate may be blackened by a luminescence phenomenon which may appear in the liquid if it contains gas. A luminescence effect of this sort was first observed in the case of pure water by Frenzel and Schultes (150), and ascribed to the production of electrical voltages in the manner of the Lenard effect during the formation of bubbles. This production of light could be photographed directly. It could be increased quite considerably when Heyden's X-ray intensifier compound was added to the water. Fig. 146 (*a*) shows the result of a 90-minute exposure of the water carrying ultrasonics, without addition, and fig. 146 (*b*) the same with addition of intensifier. The dappled appearance is a consequence of the lens effects of numerous drops of water thrown down on the protective layer of the plate. No luminous effects were seen in gas-free water. Chambers (108) has recently observed a luminescence always appearing when cavitation occurred in the case of fourteen liquids carrying waves of frequency 1000 to 9000 Hz. The light, which could be seen by the eyes after some time in the dark, was most marked in the case of glycerine and nitrobenzol.

We will conclude this section by dealing with some effects of

ultrasonics which are more of an electrochemical character. Marinesco (314) already observed that intense ultrasonic radiation changes the electromotive force of a cell when it falls on a plate forming one of the electrodes ; the effect is as if the solution pressure of the metal were increased. Young and Kersten (481) generated a stationary sound wave of frequency 1700 kHz during

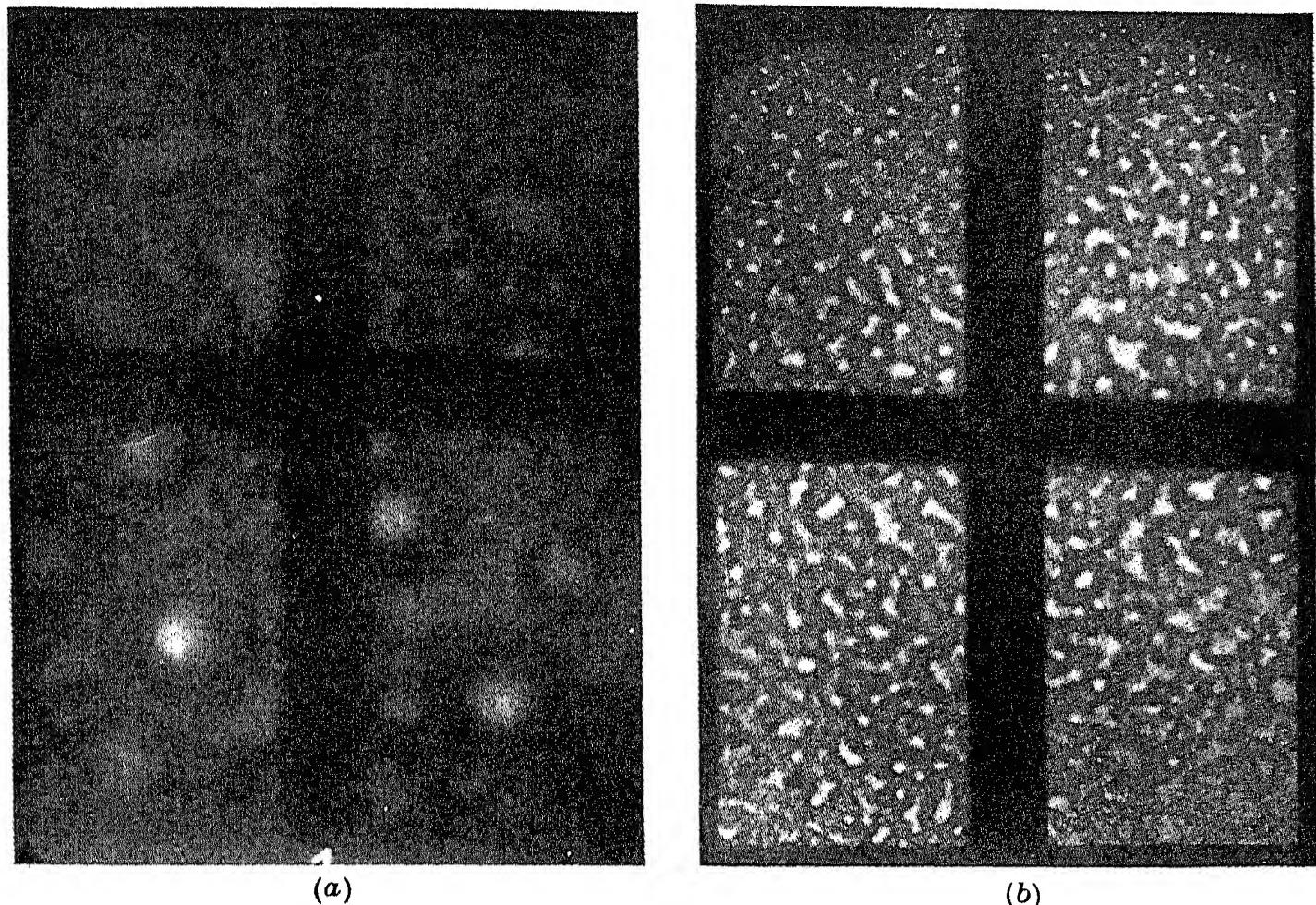


FIG. 146. Luminescence of water traversed by ultrasonics, (left) without, (right) with addition of Heyden's intensifier (Frenzel and Schultes).

electrolysis in a direction parallel to the surface of the cathode, and found that the metal separated on the cathode was rippled, the distance apart of the crests being half the wave-length of the sound. They concluded from this effect that changes in concentration of the metallic ions occur in the nodes and loops of the stationary sound wave. This agrees to a certain extent with considerations put forward by Debye (125). When ultrasonic waves are propagated in an electrolyte, there is no difference between the velocity of the ions and of the liquid when friction alone is taken into account. But if the inertial forces are also

considered, the ions lag somewhat behind the motion of the liquid particles, this lag being the greater the mass of the ions. If, therefore, we have two sorts of ions of different mass present in the liquid, we necessarily get periodical concentrations of charge in the sound wave, and hence also periodical changes in potential, which are a measure for the difference in mass of the two ions. The calculation gives, for example, in the case of a 0.001N KCl or LiBr solution, at a velocity of 1 cm per second, easily attained with weak ultrasonic waves, potential differences of the order of 1 millivolt, which lie within the range of possible measurement. This theory of Debye has been extended by Oka (335, 336), taking into account the forces between the ions, the Debye-Falkenhagen relaxation forces, and the electrophoretic forces.

(i) **The Thermal Effects of Ultrasonics.** In an ultrasonic field in a liquid considerable rise of temperature may take place, often amounting to some degrees a minute in a vessel of normal size. This development of heat results from the absorption of the sound waves in the liquid or other substance through which they are going. Dognon and Biancani (129) observed the rise of temperature produced by a certain intensity of sound in ten seconds in 2 cc of liquid of different sorts :

Water . . . .	2°	Gelatine solution . . . .	1°
Alcohol . . . .	3.5°	Gelatine gel . . . .	1°
Glycerine . . . .	10°	Stearic acid . . . .	36°
Liquid paraffin . . . .	10°	Wax . . . .	44°

We are struck by the fact that very viscous gelatine solution and even the gelatine gel are not more warmed than water, although one would expect a greater absorption in gelatine. The reason for this is probably the absence of bubble formation in the gelatine solution as compared with water, giving us less absorption of sound in spite of greater viscosity.

This development of heat in ultrasonic fields very frequently puts great difficulty in the way of investigating other ultrasonic effects, and the separation of these from thermal processes is possible only by parallel experiment with ultrasonics, but with heating produced to the same extent in another way. In this connection we have to take care that the vibrating quartz sends no heat directly into the liquid, and that all generation of heat in the liquid by the dielectric effect of stray fields from the oscillator is

avoided. Richards (379 *a*) points out these sources of error, and describes suitable methods of screening.

The generation of heat at the boundary surface of two substances traversed by ultrasonics is especially strong. Experiments of Freundlich, Söllner, and Rogowski (152) showed that a greater quantity of heat was developed in a certain amount of oil in ultrasonic waves when the oil contained small spheres of glass or shot, the heat produced increases for the same weight of shot as the radius of the latter gets smaller—that is to say, as the boundary surface between shot and oil increases.

Wood and Loomis (475) found in their first experiments with powerful ultrasonics that it is impossible to hold a thermometer dipping into an oil bath with ultrasonics in the hand, because the heat generated by friction between the glass and the fingers is too great, although the temperature shown by the thermometer may be only 25°. If we take a thread of glass a few tenths of a millimetre thick, having a small sphere on the end, between the fingers, and dip the sphere into the ultrasonic field, the thread of glass will burn a groove in the skin of the finger. In order to increase this effect, Wood and Loomis drew off the neck of an Erlenmeyer flask in the blowpipe, and melted it down to a glass rod about 0.5 mm thick. If the flask is put into the oil bath of an ultrasonic generator (fig. 147), the high-frequency vibrations are concentrated by the glass into the point of the flask. If a piece of wood is pressed against the glass point, a hole is bored in it to the accompaniment of smoke and sparks. A plate of glass may also be bored in the same way with the production of powdered glass and small spheres of melted glass, which are a proof of the heat developed. If the point of the glass rod in which the sound is concentrated is heated by a flame, the glass melts the moment it becomes red-hot, and is blown away explosively. The reason for this is as follows: In the cold condition the glass conducts the sound wave without being sensibly warmed, but when it is heated until soft, its sound absorption increases to such an extent that a considerable amount of heat is developed in the small volume, and causes sudden melting of the glass. If a glass rod is

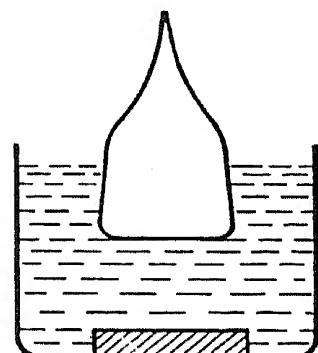


FIG. 147. Arrangement for concentrating ultrasonic vibrations (Wood and Loomis).

dipped vertically in the vibrating oil bath, stationary longitudinal elastic vibrations are formed in the rod. If a bit of easily melted wax is put on the end of the rod it melts on account of the heat produced by friction and runs down the rod. Some of the wax then remains at the nodes in the rod, so that in this way the stationary sound waves may be made visible. In the same way the ultrasonic vibrations produced in glass plates may be rendered visible as sound patterns by a coating of wax, by which they are permanently fixed.

It remains to be seen what practical applications may be found for the heating effects of ultrasonics. Freundlich, Söllner, and Rogowski (152) have proposed to use it in medicine for diathermy.

They were able to show that the marrow of a bone may be heated without the bone itself being affected. It was also possible to conduct the sound energy through the joint. Only further experiments can decide whether this form of ultrasonic deep therapy may be used to supplement the electrical diathermy method hitherto used.

A certain difficulty arises in transmitting the ultrasonic vibrations to the part needing treatment. Several possibilities present themselves. One is to immerse the body to be treated in a bath of liquid traversed by powerful waves, another is to lead the high-frequency sound energy through suitably bent glass rods to the desired position. The latter is, however, subject to a considerable energy loss. Fig. 148 shows a section of an ultrasonic generator built by the firm Société S.C.A.M. in Paris, intended for transmitting ultrasonics to the skin, etc. In the lower part *A* of the case, which is of metal, there is a piezoquartz *Q* in an air chamber *D* (see p. 37). The current is led to it through the case, and through the insulated electrode *E*. At the upper opening *C*, there is a thread to which tubes *R*, which may be of different length, are screwed; they are closed at the end by a thin metallic membrane *M*, and also completely filled with oil. The whole apparatus is set with the membrane on the body to be handled. So far no practical experience with this apparatus is given in the literature.

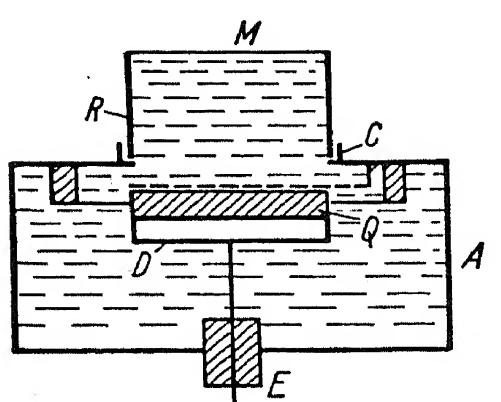


FIG. 148. Ultrasonic generator of the firm Société S.C.A.M. Paris for medical and biological purposes.

The body to be treated in a bath of liquid traversed by powerful waves, another is to lead the high-frequency sound energy through suitably bent glass rods to the desired position. The latter is, however, subject to a considerable energy loss. Fig. 148 shows a section of an ultrasonic generator built by the firm Société S.C.A.M. in Paris, intended for transmitting ultrasonics to the skin, etc. In the lower part *A* of the case, which is of metal, there is a piezoquartz *Q* in an air chamber *D* (see p. 37). The current is led to it through the case, and through the insulated electrode *E*. At the upper opening *C*, there is a thread to which tubes *R*, which may be of different length, are screwed; they are closed at the end by a thin metallic membrane *M*, and also completely filled with oil. The whole apparatus is set with the membrane on the body to be handled. So far no practical experience with this apparatus is given in the literature.

(j) The Biological Effects of Ultrasonics. The biological effects of ultrasonic waves have been the subject of a great number of investigations, which, however, can be only noticed shortly in this volume.\* If we recollect the various effects of ultrasonics so far discussed, strong dispersive power, degassing processes, cavitation, thermal and oxidizing effects, and when we remember that the particles of liquid in the ultrasonic field carry out motions which are very frequent, fast, and above all of great acceleration, it is easy to see that they must produce some effect on small animals and plants in the liquid. Langevin, and Wood and Loomis (475) already found that smaller animals, fish, frogs, etc., were lamed or killed in the ultrasonic field. Protozoa (Infusoria and the like) were destroyed (57, 343, 422). Schmitt and Uhlemeyer (422) found that the chief reason for this destructive effect of ultrasonic waves is the formation of gas bubbles. If this formation of bubbles were prevented by increase of external pressure, the destruction of the protozoa was diminished. Johnson (237) also comes to the same conclusion. The great differences of pressure resulting from cavitation led to the cell membranes and the smaller micro-organisms being torn to pieces. Red blood corpuscles were also destroyed (189, 341, 474, 475). Harvey and Loomis observed the action of ultrasonics under the microscope, and found that the cells, at first round, were distorted and stretched, losing their colour in the process, and that they were finally broken up and dispersed into a number of small spherical particles. Harvey and Loomis also investigated the effect of ultrasonic waves on the cells of the plant *Elodea* (common water weed); the ultrasonic waves cause the generation of strong eddies in the cells, and finally the protoplasm or chloroplast is separated from the cell wall and coagulated in other places. Long plant cells and algae are torn in pieces.

The effect of ultrasonics on the hearts of cold-blooded animals is described in a short communication by Förster and Holste (143 a). The amplitude is diminished and the frequency increased, and the action currents are also changed. These effects could not be obtained by the use of heat.

The effect of ultrasonic waves on bacteria and pathogenic organisms is very various. In some cases increased agglutination

\* The reader particularly interested in these questions may be referred to Dognon and Biancani, *Ultra-Sons et Biologie* (Paris, 1937).

and diminution in virulence were observed, at other times the opposite effect (221, 222, 471). Yeast cells lose their power of reproduction when exposed to ultrasonics (40, 143 *a*), luminous bacteria their luminosity (189, 190). The growth of colon bacilli could not be influenced even by a considerable exposure to ultrasonic waves of high energy. The effect of ultrasonics on the mosaic virus of tobacco was investigated by Takahashi and Christensen (456) and also by Stanley (440). The first found the sound waves to have a powerful deactivating effect, while Stanley found that this only occurred when the virus contains impurities and the liquid is not degassed. When cavitation is absent, there is no reduction in activity produced by the ultrasonic waves. Gaines and Chambers (160) have proposed to sterilize milk by ultrasonics. Further investigations are given in the bibliography (59, 60, 109, 110, 186, 187, 188, 191, 342, 419, 420, 473, 474, 476).

While all these biological effects of ultrasonics are very interesting, it is very difficult to form correct conclusions about the processes taking place. All the phenomena are complicated by the local generation of heat always appearing in ultrasonic fields, and certainly in part responsible for the biological effects (58). In any case, we have here a wide and promising field of research for biology.

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